FINAL REPORT

Title: Fire and Smoke Model Evaluation Experiment (FASMEE)

JFSP PROJECT ID: **15-S-01-01**

December, 2019

Roger Ottmar
U.S. Forest Service, PNW Research Station

Sim Larkin
U.S. Forest Service, PNW Research Station

Tim Brown
Desert Research Institute

Nancy French
Michigan Technological University

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List of Abbreviations and Acronyms

ALS	Airborne Laser Scanning
BB-FLUX	Biomass Burning Flux Measurements of Trace Gases and Aerosols
CAWFE	Atmosphere-Wildland Fire Environment model
CMAQ	Community Multi-scale Air Quality modeling system
Consume	Model for predicting fuel consumption and emissions
Daysmoke	Empirical-statistical plume-rise and dispersion model
DBH	Diameter at Breast Height
DoD	Department of Defense
EPA	Environmental Protection Agency
ESTCP	Environmental Security Technology Certification Program
FAA	Federal Aviation Administration
FASMEE	Fire and Smoke Model Evaluation Experiment
FBE	Fire Behavior and Energy
FCCS	Fuel Characteristic Classification System
FEPS	Fire Emission Production Simulator
FFE-FVS	Fire and Fuels Extension of the Forest Vegetation Simulator
FFT	Fuel and Fire Tools
FIA	Forest Inventory Assessment
FIREChem	National Aeronautics and Space Administration (NASA) wildland fire tropospheric chemistry project
FIRETEC	Physics-based computational fire behavior model
FIREX-AQ	Fire influence on regional and global environments experiment – air quality (National Aeronautics and Space Administration)
FIREX Fire	Fire influence on regional and global environments experiment (National Atmospheric and Oceanic Administration)
FlamMap	Fire behavior mapping and analysis program that computes potential fire behavior characteristics
FOFEM	First Order Fire Effects Model
FRE	Fire Radiative Energy
FRED	Fire Radiative Energy Density
FRFD	Fire Radiative power Flux Density
FRP	Fire Radiative Power
FTIR	Fourier Transform Infrared spectroscopy
Fuel3D	Three-dimensional fuel modeling system
FON	Funding Opportunity Notice
FUSION	LiDAR analysis and visualization software
FVS	Fire Vegetation Simulator
GEOS-CHEM	3-D chemical transport model
G-LiHT	Goddard's LiDAR, Hyperspectral and Thermal Imager

HYSPLIT	Simple air parcel trajectory model
IFTDSS	Interagency Fuel Treatment Decision Support System
IR	Infrared
JFSP	Joint Fire Science Program
LiDAR	Light imaging, Detection And Ranging
MesoNH-ForeFire	Mesoscale atmosphere model
NASA	National Aeronautics and Space Administration
NF	National Forest
NOAA	National Oceanic and Atmospheric Administration
NOI	Notice of Intent
NSF	National Science Foundation
O_3	Ozone
OR DOGAMI	Oregon Department of Geology and Mineral Industries
PM	Particulate Matter
PNW	Pacific NorthWest
RxCADRE	Prescribed fire Combustion Atmospheric Dynamics Research Experiment
SEMIP	Smoke and Emissions Model Inter-comparison Project
SERDP	Strategic Environmental Research and Development Program
TLS	Terrestrial laser scanning
UAS	Unmanned aircraft systems
WE-CAN	Western wildfire Experiment for Cloud chemistry, Aerosol absorption, Nitrogen
WA DNR	Washington Department of Natural Resources
WFDS	Wildland-urban interface Fire Dynamics Simulator
WRF	Weather Research Forecasting model
WRF-Chem	Weather Research and Forecasting model coupled with CHEMistry
WRF-SFIRE	Combination of the weather research and forecasting model (WRF) with a fire code invoking a surface fire behavior model (open source)

Keywords: Smoke modeling, fire modeling, large fire experiments, fuel, fuel consumption, fire behavior, energy release, plume rise, smoke transport and dispersion, smoke chemistry

Acknowledgements

FASMEE gratefully acknowledges the support of the Joint Fire Science Program and the Strategic Environmental Research and Development Program. FASMEE also acknowledges the expertise and consultation provided by the Phase 1 Science Leads and Technical Specialists to complete this document, including:

Phase 1 Science Team Leads:

Kirk Baker, U.S. Environmental Protection Agency
Craig Clements, San Jose State University
Matt Dickinson, U.S. Forest Service
Andy Hudak, U.S. Forest Service
Adam Kochanski, University of Utah
Rod Linn, Los Alamos National Laboratory
Yongqiang Liu, U.S. Forest Service
Ruddy Mell, U.S. Forest Service
Susan Prichard, University of Washington
Brian Potter, U.S. Forest Service
Shawn Urbanski, U.S. Forest Service
Adam Watts, Desert Research Institute

Technical Specialists:

David Grimm
Kevin Hiers
Derek McNamara

We wish to thank the integration and cooperation of the U.S. Forest Service, Desert Research Institute, Michigan Tech Research Institute, National Oceanic and Atmospheric Administration and National Aeronautics and Space Administration FIREX-AQ project, Environmental Protection Agency, and the National Science Foundation.

FASMEE also acknowledges contributions from host agency representatives from the US Forest service R-4, Fishlake National Forest and Richfield Ranger District (Jason Kling, Linda Chappell, Russell Ivie, Kelly Cornwall, Brian Van Winkle), North Kaibab Ranger District and Grand Canyon National Park (Dave Robinson, Casey Teske), Fort Stewart (Jeff Mangan), and Savannah River Site (John Blake).

Abstract

The Joint Fire Science Program (JFSP) and the Environmental Security Technology Certification Program (ESTCP) initiated the Fire and Smoke Model Experiment (FASMEE) (https://sites.google.com/firenet.gov/fasmee/) by funding Project 15-S-01-01 to identify and collect a set of critical measurements that will be used to advance wildland fire science knowledge and fire and smoke modeling capabilities. The project provided core leadership that developed a robust study plan and costing for a field campaign that would gather a novel set of observations, evaluate a selected set of models and use this information to advance operationally used fire and smoke modeling systems. FASMEE, with the support of the JFSP, leveraged several agency resources including the US Forest Service, National Science Foundation (NFS), National Oceanic and Atmospheric Administration (NOAA) and National Aeronautics and Space Administration (NASA) to successfully initiate the western wildfire campaign, the first of three data collection campaigns identified in the FASMEE study plan.

FASMEE was portioned into three phases including analysis and planning (Phase 1), data collection (Phase 2), and future improvements (Phase 3). Phase 1 is complete, with the study plan as the main deliverable. The plan includes science questions, data measurements and specifications, and burn recommendations that serve to guide planning. The plan has been published in the scientific literature with a second, more detailed review draft that will be published and distributed as a Pacific Northwest Research Station General Technical Report. The team also provided the Notice of Intent and the Funding Opportunity Notice for the data collection participation request and has presented FASMEE at symposia, conferences and training sessions. Finally, the western wildfire campaign was initiated as part of the data collection Phase 2 with the development of a fuels map based on airborne LiDAR, initial field data collection, and modeled source characterization for wildfires flown by the National Science Foundation supported WE-CAN and BB-FLUX projects in 2018 and eventually for the NOAA and NASA FIREX-AQ project in 2019. Specific deliverables for this JFSP project include:

1) Provided overall leadership of FASMEE through the planning and design Phase 1;
2) In conjunction with JFSP, leveraged FASMEE with other partners including the Forest Service, NSF, NOAA, NASA, EPA and SERDP;
3) Interviewed key scientists and established a science and modeling team that identified observational measurement requirements and core models to be used for validating the experimental design;
4) Identified host agencies and data collection research sites for Phase 2;
5) Developed a NOI and FON for the initial modeling and observational design work;
6) Identified requirements and a team to oversee the logistical and planning of Phase 2;
7) Completed, submitted, and distributed a final FASMEE study plan that has been published in the peer reviewed literature with a more detailed draft in the review process for publishing as a PNW General Technical Report; and
8) Developed a LiDAR fuels map and modeled the source characterization of wildfires flown for smoke measurements by the WE-CAN, BB-FLUX, and FIREX-AQ projects in 2018 and 2019 as part of Phase 2 Western Wildfire Campaign data collection.

1. Objectives

Fire and smoke models are critical tools for wildland fire decision-making and planning. However, many models that currently drive the operational systems in use today lack suitable foundational data, thereby compromising their reliability (Alexander and Cruz 2013, Cruz and Alexander 2010). As a consequence, the limits of applicability and expected errors are not defined for many models, and their use may not be realistic under specific conditions (Yao et al. 2014). Accurate estimates of fire and smoke emissions and dispersion from wildland fires are highly dependent on reliable characterization of many variables including: area burned, preburn biomass of fuelbed components and condition, fuel consumption by combustion phase, fire behavior, heat-release, plume dynamics, meteorology, and smoke chemistry. Improving estimates of plume rise, smoke production, and dispersion are fundamentally based on characterizing fire-atmosphere interactions, including fuel conditions, wildland fire behavior, and smoke plume dynamics. The Fire and Smoke Model Evaluation Experiment (FASMEE) (https://sites.google.com/firenet.gov/fasmee/) is designed as a large-scale, multi-agency study to fulfill the need for foundational data for fire and smoke modeling by identifying and collecting critical measurements. The aim is to advance wildland fire science and modeling capabilities for improved suppression operations and increased use of managed fire.

The overall goal of FASMEE is to evaluate and advance operationally applicable fire and smoke modeling systems and their underlying scientific models and frameworks. The main objective of this initial effort, as presented in this final report, is to provide critical guidance and oversight to produce a complete and validated final study plan for the FASMEE field data collection effort, and to initiate data collection and modeling for the western Wildfire Campaign.

To meet this goal, 3 major sub-objectives were identified including:

- Collect, reduce, and make available a set of quality-controlled and integrated measurements during Phase 2;
- Assure data quality, access, and value with proper data collection, management, and organization within an appropriate data access system; and
- Use data collected during the observational campaigns to improve and expand operational fire and smoke modeling.

As outlined in the study plan, FASMEE was partitioned into three phases:

- Phase 1—The analysis and planning process to review and assess the current state of fire-plume-smoke modeling and scientific understanding to determine the critical needs and realistic pathways to addressing these needs.
- Phase 2—Implementation of a set of three field campaigns (Western Wildfire Campaign, Southwest Campaign, and Southeast Campaign) to be completed over 2019-2022 to collect data valuable for model evaluation and improvement.
- Future Improvements—Identified set of analyses and improvements to models based on the data

The main deliverable of Phase 1 was the development of the FASMEE study plan (Ottmar et al. 2017) along with a Notice of Intent and Funding Opportunity Notice. The research effort was funded by the JFSP and the Department of Defense (DoD) Environmental Security Technology Certification Program (ESTCP). Following the design outlined in the study plan, the Phase 2 Western Wildfire Campaign was initiated as "additional work" under the 15-S-01-01 agreement with the JFSP. This additional work was funded and supported by JFSP and USDA Forest Service to assist in the execution of several planned campaigns by other federal agency programs and investigations to gather fuels data in coordination with airborne data collections in 2018 and 2019. In addition to this final report, FASMEE was presented at several conferences, symposia and Rx training venues during 2016-2019, and results were documented in two research articles (Liu et al. 2019, Prichard et al. 2019). Prichard et al. (2019) presented an overview of FASMEE and discussed the need for FASMEE for motivating improvement in fire and smoke modeling capability for both science and operational application. Liu et al. (2019) presented the modeling activities conducted in Phase 1 to identify major fire behavior and smoke modeling issues and the most critical observational measurements to fill modeling gaps. A third publication is a more detailed accounting of the FASMEE study plan. It is in the review process and will be published as a Pacific Northwest Research Station General Technical Report. These papers, along with this report, provide comprehensive documentation of this unique and valuable project.

The FASMEE project was conceived and initiated with guidance from the Joint Fire Science Program (JFSP) smoke science plan (Riebau and Fox 2010), a JFSP-sponsored smoke workshop synthesis, and the success of the Prescribed Fire Combustion and Atmospheric Dynamic Research Experiment (RxCADRE). By directly and indirectly influencing improvements to operational fire and smoke models, results from FASMEE will guide:

- The land management community, through improved models and guidance on their performance, reliability, scope of applicability, and validation;
- The scientific community, through a unique dataset and new understanding of fire, fire effects, emissions, and smoke plumes, chemistry, and transport; and
- The public, through improved fire information and smoke impact warnings.

This final report reviews the FASMEE project planning and design process to develop the studies concept and science plan. It will also provide initial progress on data collection and wildfire source modeling that was part of the Phase 2 Western Wildfire Campaign data collection.

Specific progress to date as presented in this final report include:

- Provide overall leadership of FASMEE through the planning and design of Phase 1 (complete);
- Interview key scientists and establish a science and modeling team that will identify observational measurement requirements and core models to be used for validating the experimental design (complete, 30+ scientists interviewed);
- Identify host agencies and data collection research sites for Phase 2 (complete);

- Develop a NOI and FON for the initial modeling and observational design work (complete);
- Identify requirements and select a science team to oversee the logistical and planning of Phase 2 (complete);
- Draft, submit, and distribute a final FASMEE study plan. Publish as a peer reviewed papers followed by a more detailed review draft submitted as a PNW General Technical Report (complete);
- In conjunction with JFSP, leverage FASMEE with other partners including the Forest Service, NSF, NOAA, NASA, EPA and SERDP (complete); and
- Develop a LiDAR fuels map and model the source characterization of wildfires flown for smoke measurements by the WE-CAN, BB-FLUX, and FIREX-AQ projects in 2018 and 2019 as part of the FASMEE Western Wildfire Campaign data collection (data reduction completed and distributed to WE-CAN and BB-Flux leads; FIREX-AQ LiDAR map distributed with fuel data reduction in progress)

2. Background and Context

Model scenarios are used across the spectrum of operational activities in managing wildland fire. Area burned (observations, airborne and satellite imagery interpretation), fuel loading (FCCS), fuel consumption (Consume and FOFEM), fire behavior (Behave and FlamMap), smoke transport (Hybrid Single Particle Lagrangian Integrated Trajectory Model [HYSPLIT]) and dispersion modeling (BlueSky Playground) systems span a broad range of complexity and sophistication (Achtemeier et al. 2011; Andrews et al. 2005, Briggs 1969, 1971, 1972; Larkin et al. 2010; Prichard et al. 2007; Reinhardt et al. 1997, Stein et al. 2015). Complex physics-based smoke models include fire and atmosphere dynamics that drive buoyancy-induced plume rise and smoke transport. Currently, a number of fire weather forecasting models including WRF-SFIRE (Mandel et al. 2011; 2014), MesoNH-ForeFire (Filippi et al. 2009) and CAWFE (Cohen 2013; Cohen and Schroeder 2013) use simplified fire spread models and local smoke models such as Daysmoke (Achtemeier et al. 2011) to approximate the sources of heat and mass that generate the buoyant plume and smoke (Table 1). These models resolve plume dynamics but parametrize combustion-related processes to enable faster than real time simulations of landscape scale (thousands of ha) wildland fires at resolutions of hundreds of meters. In contrast, models such as WFDS (Mell et al. 2007) and FIRETEC (Linn et al. 2002) explicitly account for the processes of gas-phase combustion and vegetation consumption in addition to plume rise and smoke generation. Computational fluid dynamics models of fire-atmosphere interactions require relatively high-resolution computational three-dimensional grid cells, and the resulting high computational demand precludes their routine use on large domains.

The performance of both currently used and next-generation models need to be assessed and evaluated. This assessment will make it possible to set expectations for how well a model will perform under real-world applications, the level of model uncertainties, and the key sources of these uncertainties that need improvement. This has been highlighted in recent synthesis reports, including the Joint Fire Science Program (JFSP) Smoke Science Plan (Riebau and Fox 2010), the

Smoke and Emissions Model Intercomparison Project (SEMIP) (Larkin et al. 2012), the Fire and Smoke Model Evaluation workshop and report (Brown et al. 2014), a special session on Wildland Fire Behavior and Smoke (Prichard and Ottmar 2013), the Prescribed Fire Combustion Atmospheric Dynamics Research Experiment (RxCADRE) special issue (Ottmar et al. 2016) and the joint National Aeronautics and Space Administration (NASA) and National Oceanic and Atmospheric Administration (NOAA) Fire Influence on Regional to Global Environments and Air Quality (FIREX-AQ) white paper (Warneke et al. 2018). Successful collaborations in past field campaigns, including RxCADRE and the Department of Defense's (DoD) Strategic Environmental Research and Development Program (SERDP)-funded fine-scale combustion studies, led to the JFSP partnering with the DoD Environmental Security Technology Certification Program (ESTCP) to initiate the FASMEE planning phase (Phase 1).

FASMEE has been developed as an integrative research effort to collect a large set of observational data to evaluate and improve the scientific understanding of wildland fire and smoke models and the associated science. This large-scale interagency effort is focused on the development and evolution of modeling tools serving land and fire management needs. Essential model advancements are central to operational decisions relating to (1) fire growth and fire danger, (2) fuels consumption and emissions and other fire effects, (3) plume development and characterization, and (4) smoke effects. Improvements in the underlying understanding and overall accuracy of fire and smoke models have been repeatedly identified as important needs in the JFSP Smoke Science Plan (Riebau and Fox 2010). Other studies, such as the Smoke and Emissions Model Intercomparison Project SEMIP (Larkin et al. 2012), show that significant improvements in these areas will require novel, integrated, observational datasets that could be used to evaluate and test models and basic understanding of processes across many different types of models needed in this work including: fuels, fire dynamics, consumption, emissions, plume rise, smoke transport, and smoke chemistry.

3. Materials and Methods--FASMEE Planning and Design

The initial discussions of a much larger effort following the successful RxCADRE campaigns were initiated in late 2014. The research effort was to be funded through JFSP and would involve discipline leaders and modelers from the start. This concept and effort was coined the Fire and Smoke Model Evaluation Experiment or FASMEE. Interviews with national experts provided additional ideas on the needs for model improvement and the measurement technologies (e.g., remote sensing and field-deployed technologies) that were becoming available to conduct the large-scale experiment envisioned. These phone interviews preceded a 2016 JFSP funding opportunity notice which included an invitation to serve on a FASMEE science team, followed by the selection of four discipline leaders and four initial modeling leaders. These eight leaders and several co-leaders, along with four project leaders, comprised the science team.

The science team first met in March 2016 in Seattle, Washington and envisioned FASMEE as a three-phase project (Figure 1). Phase 1 included analysis and planning, during which the science team reviewed and assessed the state of fire-plume-smoke modeling and scientific understanding to determine critical needs and realistic pathways to address these measurement needs. Phase 1 produced the study plan, Notice of Intent, and Funding Opportunity Notice with continued leadership and final planning for Phase 2. Phase 2 is a set of field campaigns to collect data that would be completed as funding was secured. Phase 3 involves testing and improving modeling applications based on data collected in Phase 2, including recommendations for best measurement practices and a set of analyses and model improvements to inform fire and smoke management decision makers.

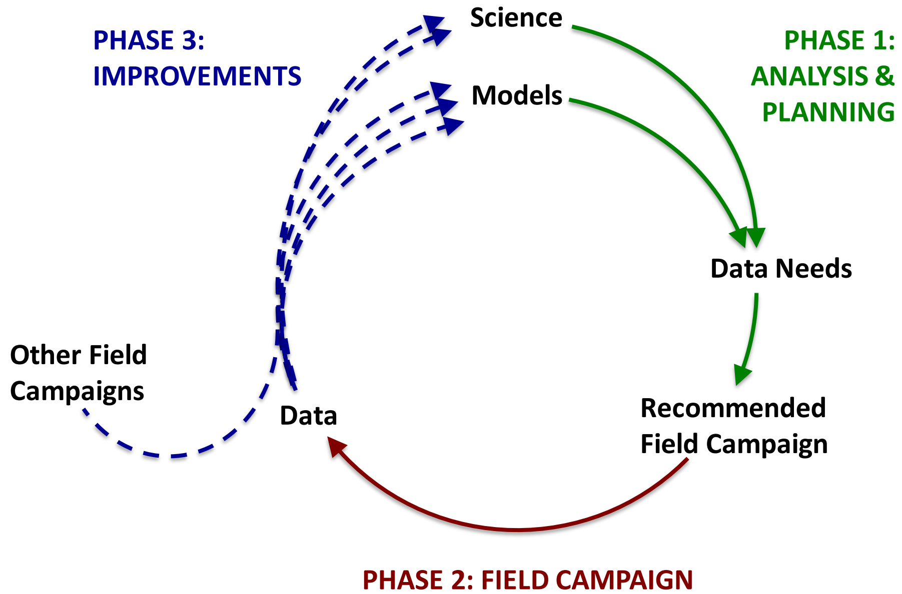

Figure 1. Fire and Smoke Model Evaluation Experiment phases include planning (Phase 1), observational data collection (Phase 2), and model improvements (Phase 3).

The FASMEE plan, as envisioned by the project leadership, was presented with options for field data collection locations and burn characteristics. This meeting included discussions about technologies available for an observational campaign, model needs, and interaction between measurement specialists for each discipline and the modelers. A decision was made on potential sites for the observational campaigns and during subsequent bi-weekly teleconferences. Subsequently, the science team visited the four selected study sites in May and July of 2016.

These site visits led to the definition of the concept that contextualizes the FASMEE experiment. The team learned of individual respective expertise, and the roadmap to develop the study plan was established. The site visits involved carrying out specific modeling tests (Liu et al. 2018), consideration of field deployment options, and considerations about how the experiments might be carried out in coordination with site managers and fire operations personnel. These site visits provided specifics on the setting and potential design of the experiment, as well as cost estimates. They were invaluable for determining a final set of priority measurements designed to benefit modeling activities.

After an extensive search for field campaign opportunities, two regions of interest in the United States (U.S.) were selected: the West, where large prescribed burns and wildfire opportunities are commonly available, and the Southeast, where prescribed fire is used extensively for resource management. The final selection of sites included stand-replacement prescribed fires in high elevation mixed conifer forests on Utah's Fishlake National Forest (termed the Southwest Campaign) and low to moderate severity prescribed underburns at Georgia's Fort Stewart (termed the Southeast Campaign). At each site, the FASMEE leadership coordinated planning with resource managers interested in assisting with the use of their site for the research purposes of FASMEE. Agency contacts expressed enthusiasm for FASMEE, making the plans viable. Even though project activities required special attention compared to typical burn operations, these resource managers found value in the planned experiment, and were willing to collaborate for a successful outcome. A third campaign was added, called the Western Wildfire Campaign. This campaign leveraged critical smoke measurements collected on wildfires by the NFS WE-CAN and BB-FLUX efforts in 2018 and the NOAA and NASA FIREX-AQ effort in 2019 with LiDAR fuel maps and modelled source characterization provided by FASMEE, with support from the JFSP.

The Phase 1 study plan details which measurements are essential to improve operational wildland fire and smoke prediction systems (systems used by land management and regulatory agencies for planning and response purposes). Research efforts focus on collecting these key measurements through the coordinated field campaigns described above and using that data to evaluate (determine a model's suitability for a given purpose) and to validate (quantitatively compare observed and predicted measurements) current and future operational modeling.

The Phase 1 study plan also establishes the needs and planning required to carry out the Phase 2 observational campaigns. Specifics related to planning, operations, logistics, and data management of Phase 2 are covered in the project report to the JFSP (Ottmar et al. 2017). The process involved model testing to help define measurement needs, and cost assessments to define a realistic level of experimental setup.

Besides the study plan document, activities of the Phase 1 science team resulted in a cohesive vision of how a large-scale experiment could be implemented. Provisions for carrying out a large experimental setup were organized with on-site resource management. Phase 1 included logistical considerations and resulted in a clear vision of how FASMEE should proceed as a multi-campaign experiment. For example, putting ample time between individual campaigns to learn implementation realities or possibly conducting the Southeast burns first, where logistics are simpler, then moving to western sites, which have more complex terrain and fuels. There were many logistical and data management requirements that need to be identified based on the data to be collected and field campaigns selected.

Finally, Phase 1 included the integration of the FASMEE concept with ongoing activities by federal research partners: National Aeronautics and Space Administration (NASA), National Oceanographic and Atmospheric Administration (NOAA), and a project funded by the National Science Foundation (NSF). This coordination was very important for 1) the continuation of FASMEE, and 2) making the federal partner efforts valuable for comprehensive modeling that has led to the initial planning of Western Wildfire Campaign activities.

Because of the interdisciplinary nature of modeling fire and smoke, the experimental structure is divided into four discipline areas:

- Fuels and consumption
- Fire behavior and energy
- Plume dynamics and meteorology
- Smoke emissions, chemistry, and transport

These areas are necessarily integrated and interrelated, and roughly follow a logical modeling progression: fuels→fire behavior→plume dynamics→smoke chemistry (Figure 2).

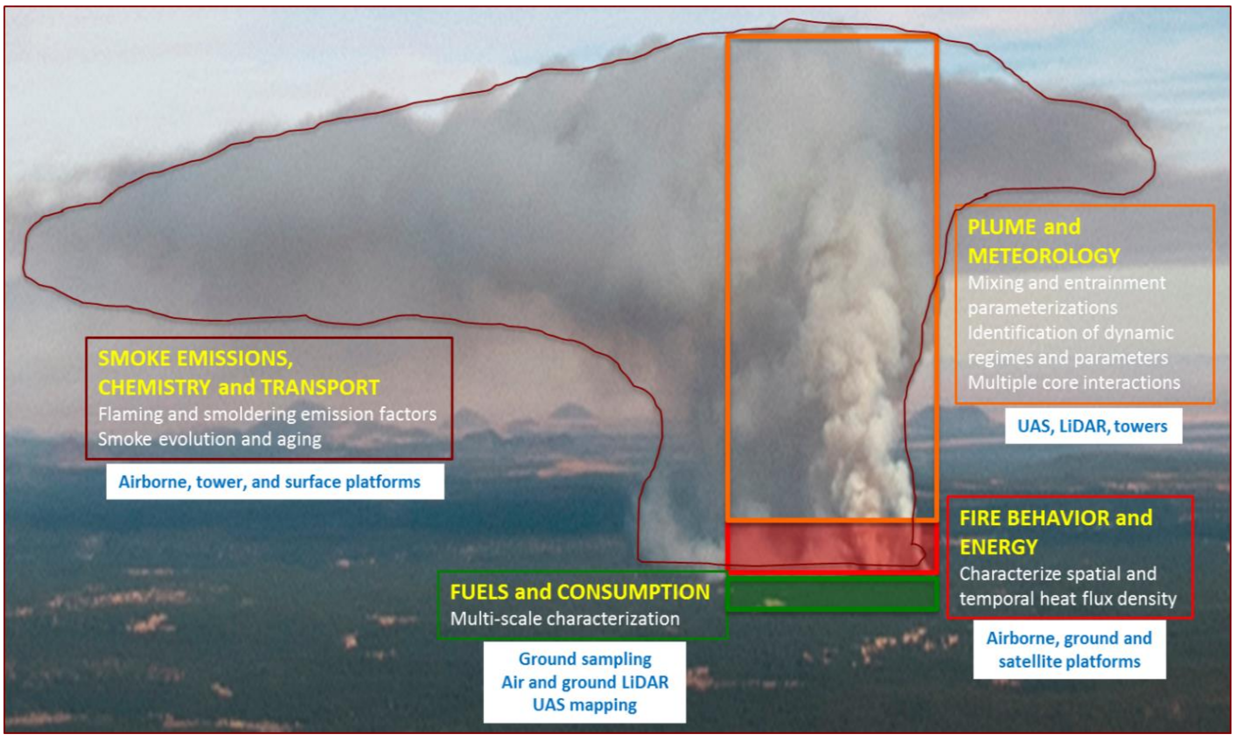

Figure 2. Graphical representation of the four Fire and Smoke Model Evaluation Experiment project disciplines.

The core organization of FASMEE and its science team is structured around these four disciplines. This structure can provide expertise needed to understand each discipline area and to effectively collaborate on a scope of work in which research needs, planned work, and analyses interconnect across disciplines. Fire effects is a fifth discipline added to FASMEE in 2019 but is not part of the deliverables for this project.

FASMEE focuses on a set of observational campaigns to collect, reduce, and archive critical, relevant, and comprehensive data of fire, fuels, and smoke over a range of spatial and temporal scales. These large-scale field campaigns will be used to:

- Test and validate the underlying scientific basis for fire and smoke models,
- Evaluate and advance operationally used fire and smoke modeling systems through quantification of key variables, to add capability and efficiency to these models, and to understand their domain of utility and applicability, and
- Provide observational context for continued fire and smoke model enhancement, including refinement and extension in fire regimes that have not been adequately characterized, including high-intensity and complex topography

To do this, progress needs to be made to:

- Improve model parameters for both model predictions and the science that serves as the foundation for the models within operational systems. For example, field measurements will help quantify processes that drive the spatial organization of fire energy and emissions which define the transition between fires and plumes and that, ultimately, determine smoke transport.
- Add capability to models to support the development of next-generation modeling systems. For example, smoke models lack a sufficient understanding of how the combustion environment combines with ambient atmospheric conditions to generate plume-driven fire dynamics.
- Improve measurements and build confidence in operational modeling capabilities and applications. This, in turn, will improve decision support for operational management.

In the end, FASMEE will be considered a success when the project:

- Improves the science that drives the fire and smoke models,
- Provides valuable knowledge that advances next-generation modeling systems and operational applications,
- Provides information on effective and cost-efficient methods for measuring fuels to be entered in fire spread, fuel consumption, and fire emissions models,
- Improves operational fire and smoke models to more accurately predict wildland fire emissions, plume dynamics, and effects on air quality; and
- Improves decision support for operational fire and smoke management.

4. Science Planning for FASMEE Implementation—Study Plan

The study plan developed during Phase 1 (Ottmar et al. 2017) presents science questions that articulate the need for FASMEE as well as data needs, burn recommendations, and measurement specifications established by the science team. During implementation of the Phase 2 observational field campaign, the study plan guides planning and operations. It will be revised and modified as individual Phase 2 projects are supported, disciplines added and logistics are refined. The plan also lays out a roadmap to complete the full circle of connections shown in Figure 1, from identifying scientific, modeling, and data needs, to conducting a field campaign, and, finally, anticipating arising needs for analysis and model improvement. The Phase 2 measurement plan is driven by scientific analyses and model improvement needs anticipated to be addressed in a later phase.

4.1 Science Questions

The overarching science question to be addressed by FASMEE as defined by the science team is:

> *How do fuels, fire behavior, fire energy, and meteorology combine spatially to determine the dynamics of near-source plumes and the long-range transport of smoke and its chemical evolution?*

This question was further broken down by the four science disciplines. Through discussions with various experts in each discipline, an interdisciplinary scientific leadership team was created to identify and organize science needs, scientific gaps and needed scientific observations for FASMEE. The resulting sub-questions by discipline are:

Fuels and consumption—

What methods can be used to measure fuels and how will the resulting measurements improve the usefulness of current and next-generation operational fire spread models, fuel consumption models, and fire emission production models?
At what spatial and temporal resolution are the methods best developed and applied?

Fire behavior and energy—

What processes drive the spatial organization of fire energy and emissions and define the transition between fires and plumes that ultimately determines smoke transport?

Plume dynamics and meteorology—

How does fire-generated buoyant flow combine with ambient atmospheric conditions to generate near-source plume organization (including plume-driven fire dynamics), establish the number of plume cores and plume entrainment, and drive the vertical distribution of smoke?

Smoke emissions, chemistry, and transport—

How do the intensity and composition of fire emissions, and their subsequent chemical evolution and transport, depend on fuel characteristics, fire intensity, combustion phase, and atmospheric conditions?

4.2 Data Needs

Addressing issues within fire and smoke modeling is challenging due to the wide array of spatial and temporal scales involved. Models typically resolve dynamics only above some minimum scale, parameterizing key variables below that scale. Operational prediction models for weather, smoke, and air quality (photochemical) generally run at scales of 1 km or greater, placing the bulk of the fire and plume dynamics into parameterized subgrid processes. Operational fire growth modeling often occurs at 30-m resolution but, at these scales, models use simplified fire growth or progression schemes that do not fully resolve complexities inherent in the underlying combustion-level dynamics and important fire-atmospheric feedbacks.

An inherent difficulty in coupled fire-atmosphere models is that appropriate scales for modeling the various components differ markedly: fire dynamics scales are much smaller than atmospheric dynamics scales. Thus, contemporary models of coupled fire and atmosphere dynamics differ considerably in their complexity and how explicitly they treat fire dynamics versus atmospheric dynamics. Models such as FIRETEC and WFDS, which explicitly model physics-based combustion, cannot routinely model low- to moderate-intensity burns over large areas (i.e. >10 ha) because of limitations in computational capability, even on large-cluster computing systems. Few measurements have been made of high-intensity, large fire events where the size and heat fluxes (defined as the sensible heat flux) can overwhelm the atmospheric background and create their own coupled plume dynamics. Of all components in the fire/atmosphere/smoke system, the least observed is the dynamic plume. Achtemeier and others (2012) modeled plumes by organizing plume cores using RxCADRE data. Although fundamentally limited, the observations of this dynamically driven portion of smoke plumes can be used to (1) evaluate, validate, or both, how current modeling systems perform; and (2) develop new modeling schema.

Simple operational plume models are based on observations of smoke stacks (Figure 3) with scaling arguments that derive area and line source equivalents. Observations of wildland fire plumes are based on either steady-state methods or they are very limited, such as light imaging detection and ranging (LiDAR) measurements of the 2013 Rim Fire (Yates et al. 2016). Lacking observations, smoke modelers have developed tuning schemes to represent the inherently non-steady-state, evolving dynamics within the plume as “plume cores” or “sub-plumes,” or they relied upon basic fluid dynamics equations without proper evaluation of their application.

The lack of a usable understanding of physical plume dynamics for modeling is a major hurdle for the variety of models seeking to address operational wildfire needs. Plume structure and dynamics are critical in relation to extreme fire behavior and predicting plume organization, particularly the entrainment and vertical lofting of smoke. For these reasons, FASMEE will focus its field collection efforts on: (1) the operational need to focus on larger wildfires, their behavior and coarse-scale smoke modeling; (2) the need for better scientific and model understanding of plume dynamics to underpin the next generation of predictive models; and (3) filling the gap of plume observations in current and past field studies.

The FASMEE project will produce one of the few databases of spatially and temporally coordinated observations of fuels, consumption, fire behavior, atmospheric conditions, plume behavior and structure, and smoke chemistry collected during high-intensity fires. By focusing on high-intensity fires, the project will provide an opportunity to develop a deeper understanding of the phenomenological differences between large, energy-intensive, operationally challenging fires and the smaller, less energy-intensive fires that are most often studied.

4.3 Priority Burns and Measurements

Based on the types of fires that have been studied previously, the data available from those fires, and the data input needs of smoke and fire models, the FASMEE science team developed a list of the types of burns that should be studied and the necessary measurements to collect during the regional field campaigns. Recommended types of burns and measurements translate the related data needs of the science questions and the models into a specific set of achievable field observations. These recommendations form the core of the FASMEE Phase 1 planning process.

Experts in fuels, fire behavior, meteorology, plume dynamics, and smoke chemistry developed the list of needed burn types and measurements. Preliminary modeling was conducted on potential burn sites, and assessments were undertaken to compare data needed for models to run along with model sensitivities and differences to determine priority measurements.

Types of burns—

The diversity of fire and smoke science disciplines represented in Phase 1 meant that a wide range of desirable burn types were discussed. For fuel characterization and consumption, heavier fuels in both eastern and western parts of the country will be required. For fire behavior modeling issues, different types of burns will be needed to resolve fire dynamics and plume dynamics. To resolve fire dynamics, smaller burns with large fireline depth, including a gradient in fuel types and terrain complexity, are desired. For plume dynamics and smoke emissions, larger fires capable of producing a signal over the noise of background meteorological conditions are essential. Preferences were narrowed through science team discussions to prioritize the type of burns desired for FASMEE to: (1) high-intensity surface and crown fires, (2) large fires capable of producing significant atmospheric plume dynamics and a substantial downwind smoke plume, and (3) where possible (particularly in the Southwestern Campaign), free-running fire (fire behavior not affected by ignition or suppression), to avoid inherent initialization issues in random ignition that does not coalesce into a freely evolving fire.

Recommended measurement suite—

Recommended measurements spanned the four interrelated disciplines of FASMEE: fuels and consumption; fire behavior and energy; plume dynamics and meteorology; and smoke emissions, chemistry, and transport. Fuel type, condition, and consumption during wildland fire relates to fire effects such as radiative heating, which provides the energy that drives fire dynamics. Another key factor in fire behavior is local-scale meteorology, which also relates to atmospheric chemistry, dispersion, and transport. Plume dynamics provides the connection between fire behavior and far-field smoke dispersion, as it determines the vertical distribution of the emissions. The quantity and speciation of emissions are determined by the variation in pyrolyzed gases and air participating in the reaction (fire behavior).

To observe the coupled fuels-fire-atmosphere-smoke system, many different instruments and platforms are needed (Figure 3). Ground, aircraft (including unmanned aircraft systems [UAS]), and satellite platforms are needed to make the necessary measurements of this system. Specific measurements are generalized by discipline.

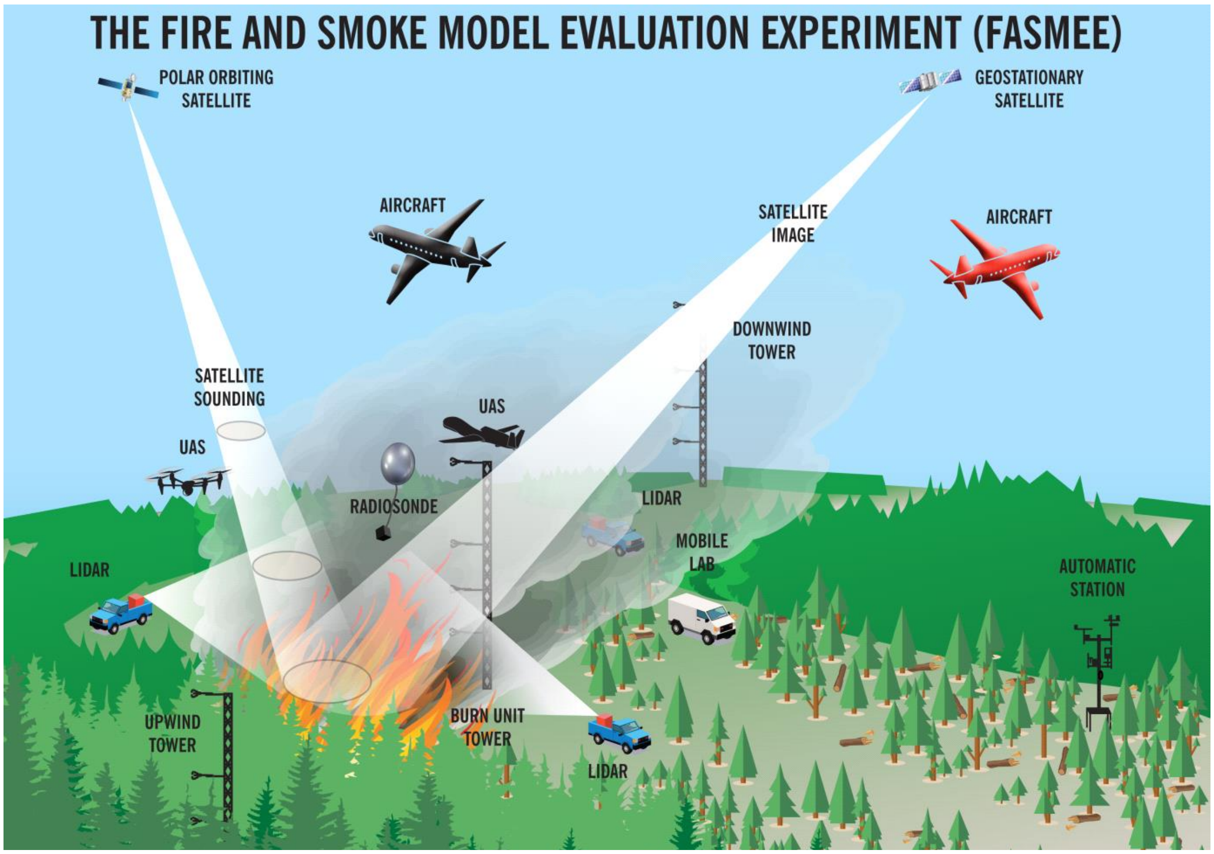

Figure 3. Schematic representation of the Fire and Smoke Model Evaluation Experiment measurement platforms.

Fuels measurements—

Fuels are the primary independent variable for all other FASMEE disciplines. Specifically, the rate of fuel consumption determines the heat release rate and other aspects of fire behavior, plume dynamics, and the gaseous and particulate composition of the smoke. Fuel consumption is most explicitly linked to fire behavior at fine scales of variability, but it also drives plume dynamics at coarser scales and spatiotemporal variation in smoke near the source (Parsons et al. 2011). Because smoke models require detailed fuel consumption information to predict heat-release rates and emissions, any field measurements of the smoke plume must include pre- and post-burn fuels information for all combustible material (trees, shrubs, forbs, grasses, coarse and fine woody debris, litter, and duff). Methods for collecting these data will include extensive field sampling linked with LiDAR. Field sampling is the most reliable method for collecting the pre- and post-fire information, but to capture heterogeneous fuel distributions, terrestrial and airborne LiDAR and structure from motion (SfM) methods for complementary point cloud data are also needed.

Key variables to be measured are fuel load by category, as well as fuel structure, composition, and moisture. These fuel properties will be measured during Phase 2 using airborne laser scanning (ALS), terrestrial laser scanning (TLS), multi-spectral imagery, thermal IR or microwave imagery, photogrammetry, and destructive and non-destructive ground measurements based on inventories of subplots and transects.

Fire behavior and energy measurements—

The fire behavior and energy (FBE) discipline provides the basis for answering key science questions related to the "handoff" of mass and energy between the fire and plume. This research can also deliver the datasets describing heat-release in space and time that are required for plume models and which provide data for evaluating fire models and underlying key assumptions of smoke models. It requires a combination of remote sensing, coordinated ground measurements, and modeling. Coordinated measurements will be stratified across their expected range of variability within and among fires, and fire heat-release rate will be characterized across space and time. This will allow description of the evolution of structure in fire heat-release and plume structure that arises because of the coupling of the fire and the atmosphere.

Key measurements for FBE include quantitative fire radiation data from satellite, airborne and tower-based platforms. Other important measurements are flame-front dimensions, spread rates and radiation, flame energy transport, emissions fluxes and combustion efficiency, and emissions partitioning between flaming and smoldering combustion. Fire radiation measurements are needed to derive spread rates, and a combination of data and modeling is needed to derive flame-exit gas temperatures, velocities, and convective fluxes in space and through time as inputs to plume models.

Plume dynamics and meteorology measurements—

Coupled fire-atmosphere models are capable of resolving spatial distribution and temporal dynamics of fire behavior, fuel combustion and smoke production rates. Plume dynamics and meteorology measurements can be organized into four measurement platforms: (1) airborne in situ observations, (2) tower-mounted in situ observations, (3) ground-based in situ observations, and (4) ground-based remote sensing. The atmospheric environment surrounding the burn unit and region is best characterized by a network of surface stations. A network of vertical atmospheric profilers around both the experimental burn unit as well as outside the experimental region is also essential to quantify both local and mesoscale circulations. Vertical profiles of winds and temperature provide measurements of atmospheric stability and shear of the fire environment, and can be helpful in predicting plume dispersion and smoke behavior. To better understand the effect of surface-layer micrometeorology on fire behavior and smoke dispersion, a suite of tall towers (30–50 m) will be placed within the burn unit. These towers can also support other instruments for measurement of FBE. Plume-rise, entrainment, and fire-atmospheric circulations associated with the plume can be directly measured using a suite of scanning Doppler LiDAR systems (ground and/or aircraft).

Key meteorological variables needed to characterize fire weather conditions and surface meteorology include ambient air temperature, humidity, near-surface wind speed, and wind direction. Unmanned aircraft systems (UAS), radiosondes, and LiDAR are needed to observe the plume dynamics and thermodynamics from above the canopy upward to several kilometers.

Smoke chemistry and transport measurements—

Emissions from biomass burning are a complex mixture of gases and aerosols. Emission factors measured must represent all phases of combustion, including flaming, smoldering, and long-term smoldering phases. A comprehensive chemical characterization of smoke emissions requires that many instruments and techniques be placed on both ground-based and airborne measurement platforms. To understand chemical evolution in the smoke plume, detailed precursor and chemical product measurements are needed in the near-field to define emission rates of key precursors as well as at different downwind distances (ideally even hundreds of kilometers from the fire source) from a fire extending over a multi-day period. Ground-based emissions measurements include gas emissions downwind of the burn, post-fire-front gas emissions from independently smoldering fuel components, and downwind point sampling of aerosol and gas emissions. Airborne chemical measurements will help researchers understand chemical evolution in the plume and obtain a more representative smoke sample than is possible using ground-based measurements, because (1) an airborne platform samples a significantly larger volume of smoke than any of the ground-based approaches, and (2) the buoyant smoke plume entrains and mixes emissions from a large area. Another advantage of an airborne platform is the ability to move instruments into the smoke.

Essential measurements for smoke chemistry and transport include particulate matter, carbon, ozone, nitrogen-containing compounds, and volatile organic compounds (VOCs).

4.4 Recommended Field Campaign Sites

Guided by these data needs and science questions, an extensive search for field campaign sites was phased in to accommodate (1) the objectives and goals of FASMEE, and (2) coordination with other agencies. Site selection originally targeted the United States and Canada but narrowed to three campaigns located in the United States. These areas were selected based on:

- Ability to meet identified logistical and scientific needs and requirements for burns and measurements.
- Interest shown by host agencies.
- Estimated cost.

- Geographic balance, with an emphasis on high-intensity fires typical of wildfires in the western United States, and prescribed underburns in pine forests of the southeastern United States with heavier surface fuel accumulations.
- Unique field and airborne campaign opportunities unlikely to be repeated in the near future.

As shown in Figure 4, the recommended field campaigns are:

- Western Wildfire Campaign—Western United States wildfires that initiate in 2018 and 2019, followed by field-deployment and modelled source characterization.
- Southwestern Campaign—Highly instrumented prescribed burns in dense mixed conifer-aspen forests, ignited for a high-intensity, stand-replacement or mixed-severity fire. Fishlake National Forest has been selected as the host agency (Figure 5) with the North Kaibab Ranger District as an alternate.
- Southeastern Campaign—Instrumented prescribed underburns in managed pine forests with heavy surface fuel loads, ignited for a moderate-intensity fire. Fort Stewart, GA has been selected as the host agency (Figure 6) with the Savannah River Site as an alternate.

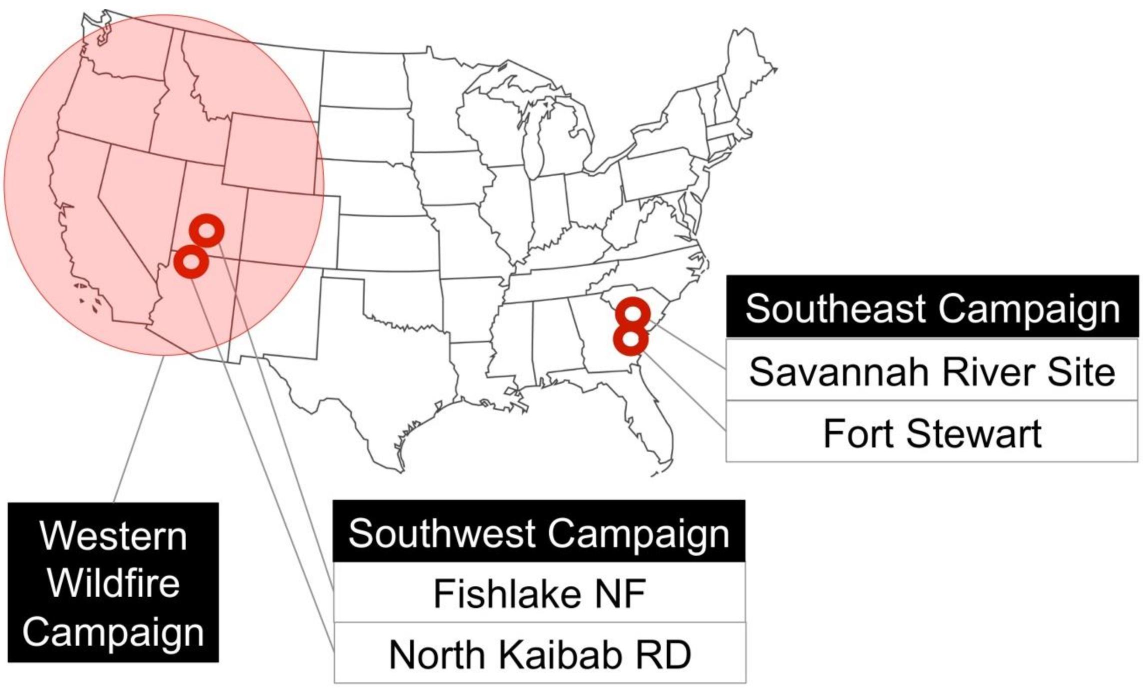

Figure 4. Fire and Smoke Evaluation Experiment-recommended field campaign sites. The western wildfire campaign will target active wildfires in the western United States **(s**haded red circle). The Southwestern Campaign will target stand replacement prescribed burn sites at Fishlake National Forest as the best opportunity, with the North Kaibab Ranger District as an alternate site. The Southeastern Campaign will target prescribed burn sites at Georgia's Fort Stewart, with the Savannah River Site as an alternate site.

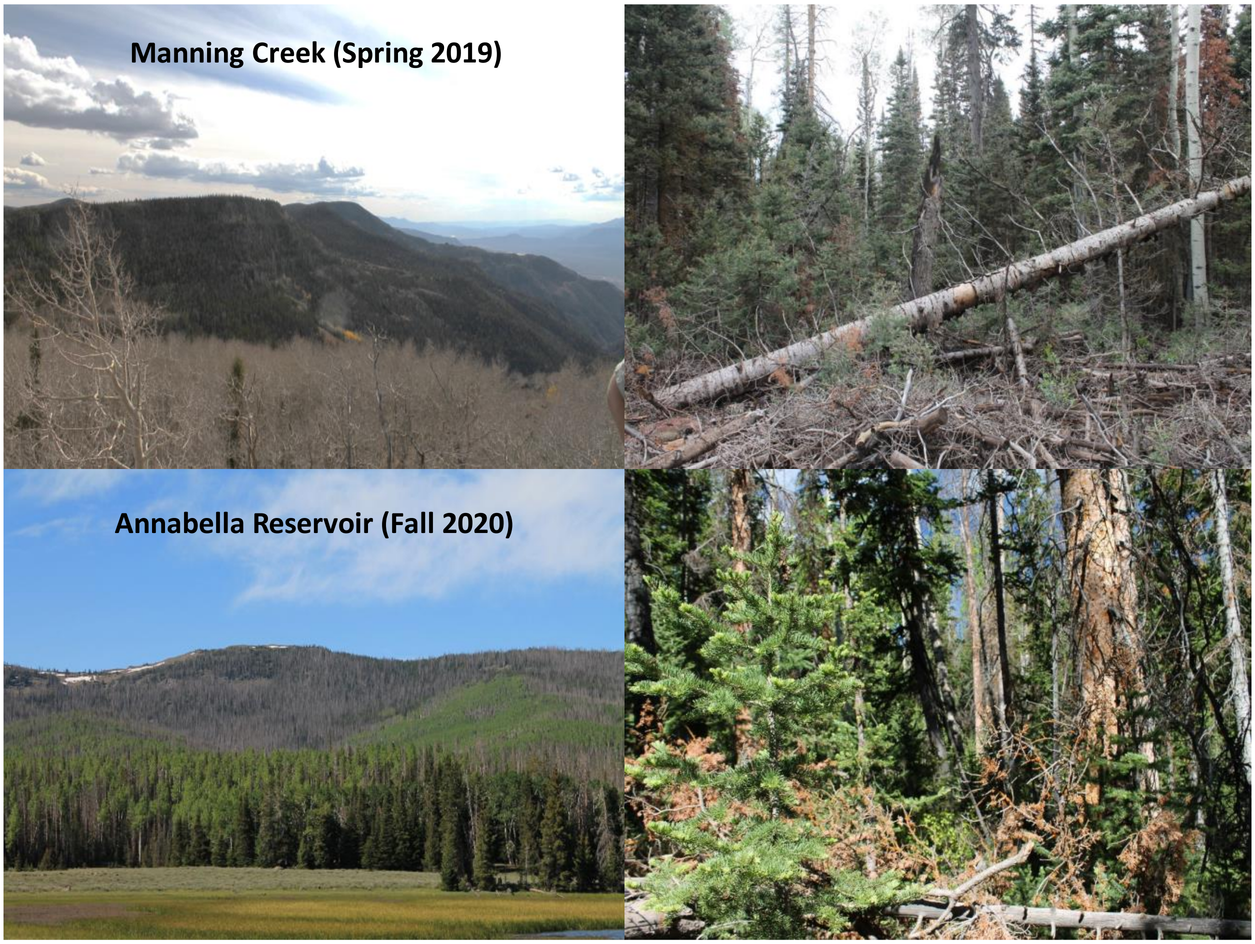

Figure 5. Manning Creek and Annabella Reservoir units selected for the southwest campaign located on the Fishlake National Forest, UT. The Manning Creek unit was burned on June 20, 2019, and sampled by FASMEE scientists. Annabella Reservoir will be burned in the fall of 2020.

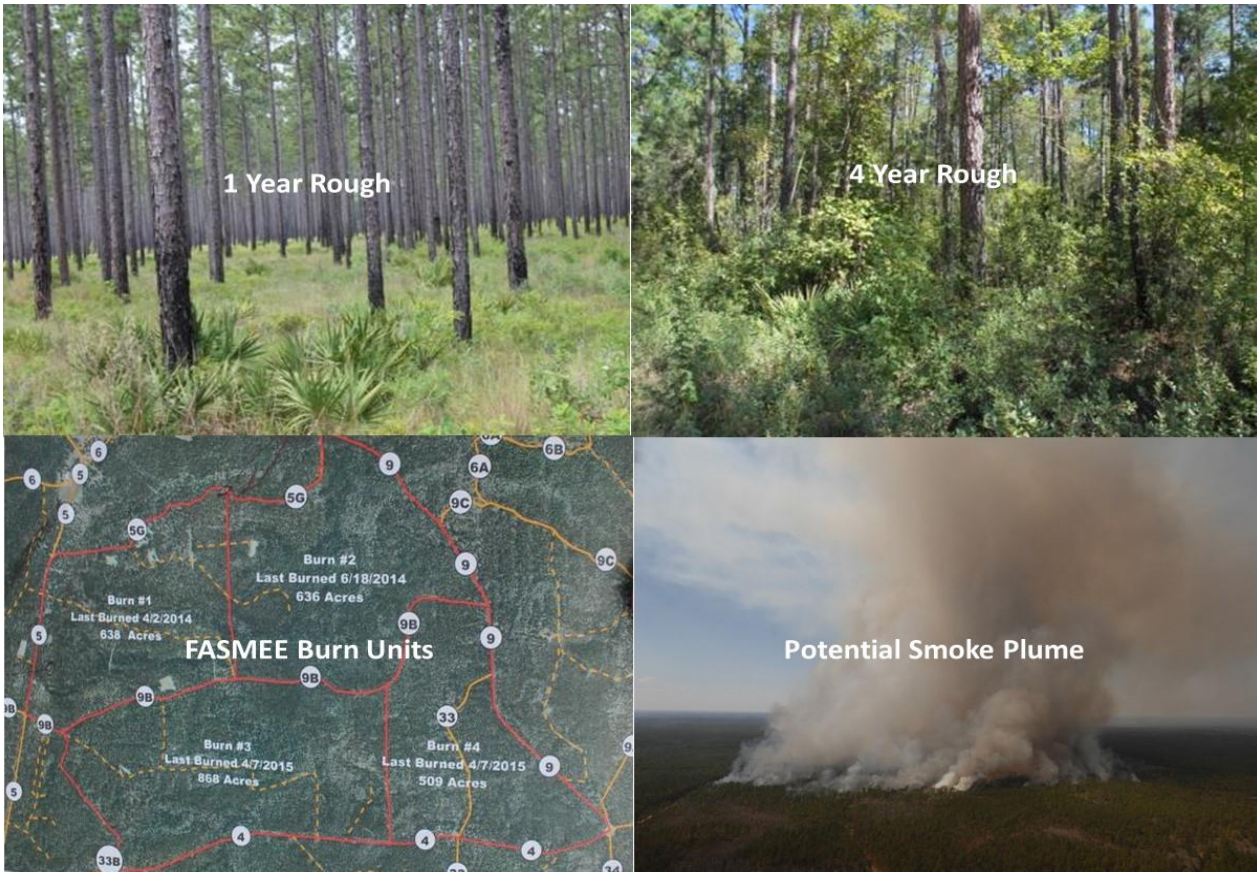

Figure 6. Four units selected for the southeast campaign located at Fort Stewart, GA. Planned burn schedule is for winter of 2021 or 2022.

5. Common Components

Any experimentally-designed field campaign must address critical common elements, ranging from safety to data quality. Ensuring safety throughout the project requires strict command structures, incident action plans, and aircraft safety plans, as well as site access and logistical staging plans. For the FASMEE study plan, these common components included (1) a specified command structure, (2) aerial and aviation guidelines, (3) an incident action plan, (4) a prescribed fire plan, (5) a logistics plan, (6) a communications plan, (7) a review of access and accountability for each site and campaign, and (8) a data management plan.

Ensuring data quality includes quality assurance, archiving, and documentation, as well as data cross-compatibility among the different measurements and platforms. In particular, measurements must be synchronized across time and space. This is especially critical for high temporal resolution measurements of the fire and plume, where failure will jeopardize the end-product usability.

6. Integration with Other Field Campaigns

The JFSP and FASMEE worked together to leverage the funding and support acquired for this project by soliciting related field studies that were acquiring complementary and additional data for evaluation and advancing of fire and smoke models. This included 1) airborne studies supported by the National Science Foundation (WE-CAN and BB-FLUX) and the NOAA and NASA FIREX-AQ project, 2) field based fire behavior and fuels studies supported by the Department of Defense Strategic Environmental Research and Development Program (SERDP), the US Forest Service PNW Research Station, and the US Forest Service Washington Office.

6.1 Integration with Complementary Airborne Smoke Studies

FASMEE is being undertaken as part of a coordinated group of field campaigns (currently in various levels of planning and implementation) on wildland fire and wildland fire smoke, including the combined NOAA Fire Influence on Regional and Global Environments Experiment (FIREX) and the NASA wildland fire chemistry experiment (FIREX-AQ) with field sampling starting in 2019, the NSF Western Wildfire Experiment for Cloud Chemistry, Aerosol Absorption and Nitrogen (WECAN) and BB-FLUX projects starting in 2018, and fire studies funded by the U.S. Environmental Protection Agency (EPA) and the U.S. DoD under their Strategic Environmental Research and Development Program (SERDP).

The FIREX-AQ campaigns and U.S. EPA and NSF research projects are aimed at advancing our understanding of smoke and how it influences the chemistry of the atmosphere.

Among these campaigns, FASMEE provides the full characterization of not only smoke plume composition but also the characteristics that generate smoke (Figure 7). This unique perspective specifically addresses all components of characterizing the fuels, fire, and plume development that influence smoke emissions and injection into the broader atmospheric circulation, as well as near-fire smoke chemistry and plume aging. To address key questions about the effect of North American wildland fires on air quality and climate, plume sampling integrated with ground-based source characterizations are needed to interpret WECAN, BB-Flux, and FIREX-AQ data. The FASMEE framework also provides expertise in characterizing fuel and fire that does not exist in either projects focused on atmospheric chemistry. The timing of FIREX-AQ and WECAN airborne sampling overlaps with FASMEE activities; thus, efforts are underway to work with these campaigns to leverage capabilities and collect data sets to fulfill the suite of objectives from all three efforts. By combining forces and using the strengths of each group, valuable measurement datasets will be publically available and enhance the value of FASMEE for smoke model improvement. Deployment of FASMEE researchers to FIREX-AQ and WECAN-sampled wildfires will allow measurement crews to test approaches and evaluate protocols, enhancing the data available to achieve the goals of FASMEE, FIREX-AQ, and WECAN. FIREX-AQ airborne resources were to be made available to sample the planned FASMEE prescribed fires in the Southwestern Campaign, but an aircraft mechanical issue prevented this. Additionally, FIREX-AQ teams have expressed interest in assisting with airborne resources for the Southeastern Campaign. The FASMEE study plan (Ottmar et al. 2017) outlines the rapid-deployment opportunities for smoke characterization, using a combination of existing ground-based and remotely-sensed datasets, on-site measurements, and modeling approaches. The study plan (app. 3) also reviews the roles of FASMEE and FIREX-AQ at the FASMEE prescribed burn sites in the Southwestern Campaign (Fishlake and Kaibab NFs) and Southeastern Campaign (Fort Stewart and the Savannah River Site).

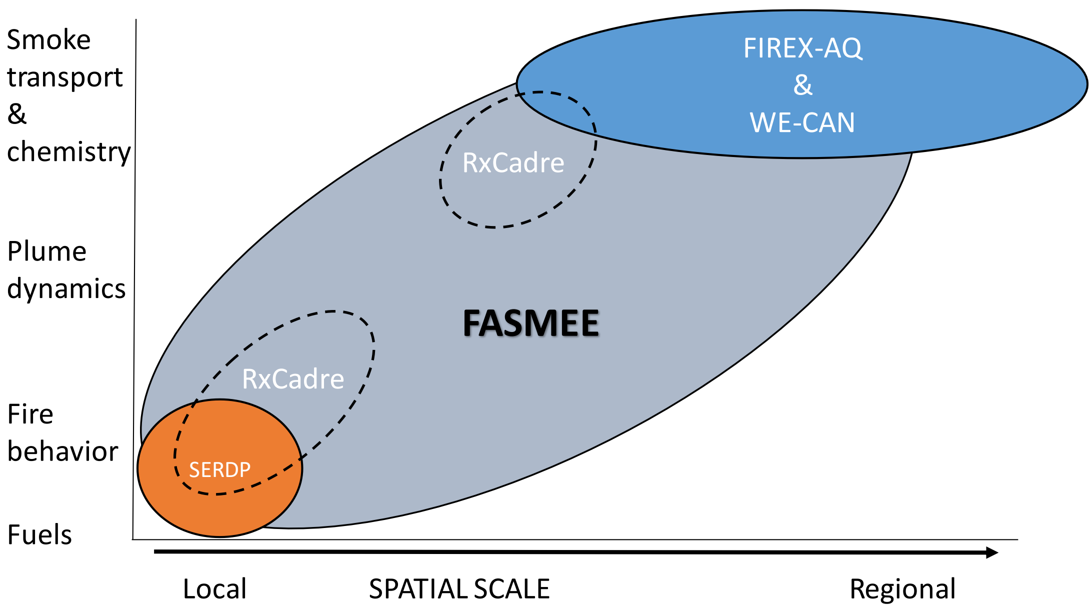

Figure 7. Conceptual diagram showing the spatial scale and discipline focus of recent and new fire and smoke field campaigns and their relationship to the Fire and Smoke Model Evaluation Experiment.

6.2 Connections Between Fire Behavior and Fuel Field Campaigns

The U.S. Department of Defense, Strategic Environmental Research and Development Program (SERDP) and Environmental Security Technology Certification Programs (ESTCP) funded similar projects on wildland fire behavior and smoke, guided by their fire science strategy (Cohen et al. 2014). In 2009, SERDP invested in several projects to advance the science of emissions factors for inclusion in EPA AP-42 (https://www.serdp-estcp.org/Featured-Initiatives/Conservation/Fire/(list)/1/). One of those projects (Advanced Chemical Measurements of Smoke from DoD-Prescribed Burns) supported field-based and laboratory measurements of the chemical composition of smoke from prescribed burning in the southeastern United States and contributed to a database of wildland fire emissions factors (Johnson et al. 2013). The ESTCP technical committee on Resource Conservation and Resilience (formerly known as the Resource Conservation and Climate Change program area) oversees a project led by Mr. James Furman and Dr. Rodman Linn to validate the numerical model FIRETEC against the RxCADRE dataset and evaluate its value for prediction of fire-atmospheric feedbacks of aerial ignitions.

Recent SERDP investment has funded eight projects to support advances in the fundamental science of wildland fire combustion. Collectively, principal investigators from these projects have been engaged for potential collaborations and applications of DoD-funded research to the FASMEE project. Ongoing laboratory and field-based studies of fine-scale combustion processes associated with vegetation types managed by the Department of Defense (DoD) Strategic Environmental Research and Development Program (SERDP) (https://www.serdp-estcp.org/Program-Areas/Resource-Conservation-and-Resiliency/(list)//(sort_by)//(sort_order)//(active)//(view_all)///(offset)/20/(list)/1) include:

- Understanding Fire Response to Spatial Variation in Vegetation Distribution and Wind Flow (Butler RC-1170)
- 3D Fuel Characterization for Evaluation of Physics-based Fire Behavior, Fire Effects, and Smoke Models on US Department of Defense Military Lands (Ottmar RC-1064).
- Characterizing Multi-scale Feedback Between Forest Structure, Fire Behavior and Effects: Integrating Measurements and Mechanistic Modeling for Improved Understanding of Pattern and Process (Hoffman RC 19-1119)
- Physics-based Modeling of Fire Behavior and Smoke Plume Development—How Much is Enough? (Mell RC 19-1132)
- Live Fuels: Identification of Key Processes Controlling Ignition and Fuel Consumption (Blunck RC 19-1092)
- Fundamental Measurements and Modeling of Prescribed Fire Behavior in the Naturally Heterogeneous Fuel Beds of Southern Pine Forests (Weise, RC-2640)
- Multi-scale Analyses of Wildland Fire Combustion Processes in Open-canopied Forests Using Coupled and Iteratively Informed Laboratory-, Field-, and Model-based Approaches (Skowronski RC-2641).
- Examination of Wildland Fire Spread at Small Scales Using Direct Numerical Simulations and Frequency Comb Laser Diagnostics (Hamlington 22642)
- Improving Parameterization of Combustion Processes in Coupled Fire-Atmosphere Models through Infrared Remote Sensing (Goodrick RC-2643)
- Ignition, Propagation, and Emissions of Smoldering Combustion: Experimental Analysis and Physics-Based Modeling (Blunck RC-2651)

The SERDP projects are designed to improve the understanding of wildland fire combustion processes. It is imperative that the larger-scale data collection of FASMEE be closely tied to the landscape-scale SERDP projects and the regional-scale smoke measurements made as part of FIREX-AQ, EPA, and NSF.

6.3 Integration with U.S. Forest Service

The U.S. Forest Service PNW Research Station and the USFS Washington office provided additional funding for FASMEE to focus on the most critical aspects of FASMEE work that fits within available funding opportunity and creates value in and of itself without critically relying on additional future funding. The goals of this work include:

- Leverage, to the highest degree possible, multiple funding sources to provide for the maximum possible benefit. In particular, the additional data being collected will make the NSF WECAN and NOAA / NASA FIREX-AQ datasets relevant to fire and smoke modeling by providing a means to relate the airborne data to fire activity, fuels measurements, and plume behavior.

- Pilot the most critical measurement sets outlined in the FASMEE study plan in order to provide a roadmap for future field campaign observations. Within the budget constraints, a full FASMEE field campaign is not feasible, but the proposed Fishlake fire experiment will record the most critical aspect of the plume dynamics measurements identified by FASMEE. This will allow an analysis that relates these measurements to fire behavior and fuels data. Doing so will provide insight into how to begin building a better plume rise model for high intensity fires.

7. Western Wildfire Campaign Approach (Additional work)

FASMEE initiated the western Wildfire Campaign by meeting with WE-CAN, BB-FLUX and FIREX-AQ leads and discussing the importance of fuels and source characterization to associate with the emission and chemistry data collected from western wildfire plumes. Our approach was three pronged: 1) compilation of LiDAR data to map fuels and use that map as one criteria for selecting wildfires to sample during the airborne campaign, 2) field data collection of fuels for selected wildfires, 3) and modelling the fuels for source characterization of wildfire sites sampled with aircraft using the Fuel and Fire Tools (FFT) software program (https://depts.washington.edu/fft/).

By September 14, 2018, approximately 30 WE-CAN and 31 BB-FLUX research flights were successfully completed for the Western Wildfire Experiment for Cloud Chemistry, Aerosol Absorption and Nitrogen (https://www.eol.ucar.edu/field_projects/we-can) and the Biomass Burning Sources project (http://ciresgroups.colorado.edu/volkamergroup/index.php/field-work/2018/bb-flux).

7.1 Methods

In September 2018, staff from the U.S. Forest Service Rocky Mountain and Pacific Northwest Research Stations, led by Dr. Andrew Hudak and Dr. Roger Ottmar, conducted field sampling for two wildfires that were successfully flown by the BB-Flux project. Sampling occurred for two additional wildfires that had successful research flights by the WE-CAN team in spring of 2019. Sites for ground sampling of fuels were selected if the plumes were successfully sampled for smoke by either WE-CAN and BB-FLUX, if there was a successful research flight from the National Ecological Observatory Network, if there was a potential for the wildfire to be flown after the fire by the G-LIGHT project, and if the wildfire was co-located with existing pre-wildfire LiDAR data for the burn perimeter.

Van Kane of the Precision Forestry Cooperative at the University of Washington acquired copies of airborne LiDAR coverages collected across the western US. This was part of a recently completed NASA Carbon Monitoring Systems (CMS) project to map aboveground biomass across the northwestern US (WA, OR, ID, western MT) from project-level LiDAR and field plot datasets contributed by stakeholders within this study region (Hudak et al., in review). This effort was expanded to the western US in 2018 with the infusion of JFSP FASMEE funding. We contacted the remote sensing coordinators in each western USFS region (1-6) to request their airborne LiDAR datasets, along with other managers of LiDAR datasets such as the WA DNR, OR DOGAMI, and tribes. The LiDAR points are being consistently reduced into canopy height and density rasters at 30m resolution, using the gridmetrics tool in FUSION software (McGaughey 2018). Within the spatial extent of forest inventory plots of fixed radius, the LiDAR points are being reduced to the same metrics, using the cloudmetrics tool in FUSION. Whereas the gridmetrics are used for mapping, the cloudmetrics are used to specify the models for predicting the fuel attributes estimated on the ground at the forest inventory plots. In the case of systematically sampled Forest Inventory and Analysis (FIA) plots that intersect existing LiDAR coverages, the point cloud data are clipped from the 4 subplots comprising each FIA plot footprint. Using a case study in Oregon, we predicted aboveground biomass, canopy fuels, and surface fuels, testing both subplot- vs plot-level models, and regression vs imputation modeling approaches. As the state with the most widespread LiDAR coverage in the western US, Oregon was particularly well suited for this study. We have found little benefit in specifying subplot-level models vs. simpler plot-level models based on the aggregated subplot data (Mauro et al. in prep). In a large number of FIA plots in Oregon which are located within available LiDAR coverages, we have found better performance with nonparametric imputation models than with parametric multiple linear regression models (Mauro et al. in prep).

We are also pursuing fuel consumption estimates for measuring smoke plume emissions and energy release at 5 wildfire sites selected by the 2018 BB-FLUX and WE-CAN campaigns and 2 wildfires by the 2019 FIREX-AQ campaign. These wildfires were selected in large part because they burned through existing LiDAR coverages. Due to this fact, the predictive fuel models we are developing can be applied to estimate pre-fire fuel loads. This reduces by half the expense to the FASMEE WWC by only requiring post-fire LiDAR and field data collection to estimate post-fire fuel loads. To date, we have collected post-fire fuel measures on the ground at 6 of the 7 wildfires, and post-fire LiDAR at 5 of the 7 wildfires, 3 of which have been delivered. A case study of 2 earlier western wildfires, where pre- and post-fire field plot and LiDAR datasets were already available, provides evidence that the best strategy for reducing model and map uncertainties is to combine the pre- and post-fire datasets into a generalized model (McCarley et al. in prep). The same strategy will be applied to the two FASMEE prescribed fires in the Monroe Mt. District of the Fishlake NF, once post-fire LiDAR are obtained in June 2020.

To characterize burned fuels, we selected areas within the burn perimeter for the day of the research flight to pair with areas outside the burn perimeter that had analogous fuel conditions. Once the sampling areas within and outside the wildfire perimeter were selected, we targeted the dominant and distinct fuelbeds Fuel Characteristic Classification System (FCCS) within FFT. .

For the most abundant fuelbeds, we installed plots to characterize the forest canopy (if present), shrubs, herbaceous, downed woody fuels, and surface fuels (i.e., litter and duff). For canopy fuels, we measured: canopy cover (%), diameter at breast height (DBH), tree height, height to live crown (HLC), tree density, crown volume scorch (%), and relative cover (%, by species). Overstory measurements occurred in 8-m radius circular plots from selected plot centers. Brown's transect lengths and intervals to measure litter/duff depths have yet to be determined. For shrubs, we measured: shrub cover (%), height, % live, % green, relative cover (by species), and biomass (by species). To characterize biomass, we clipped all vegetation within a 1-m^2 square. In sagebrush grasslands, we collected all downed woody biomass and litter separately. We transported the biomass material to the Pacific Wildland Fire Sciences Laboratory, where each sample was oven-dried, and fuel moisture calculated.


Figure 8. Fuel sampling at Keithly wildfire

The primary FCCS fuelbeds sampled for the Keithly Fire were xeric grassland and sagebrush grassland; for the Tepee Fire the main fuelbeds were sagebrush grassland and Ponderosa pine savanna (Figure 8). We installed 9 burned plots and 9 unburned plots for each fuelbed. When the field data was reduced, a customized Fuel Characteristic Classification System (FCCS) was developed that correspond with the burned and unburned fuels at each individual fire and fuelbed type. We process the customized fuelbeds through CONSUME, which resides in FFT, and generates a report of the amount of biomass that is consumed, and emissions produced during the day of the research flight.

All 27 wildfires flown by WECAN and BB-FLUX in 2018 were assessed for area burned during plume sampling, assigned FCCS fuelbeds, and nearest weather stations interrogated (Table 1). All input dates were entered into FFT and source characterization of fuels, fuel consumption, heat released and emissions produced predicted. Input and output data was entered into the WECAN data repository.

WECAN		BBFLUX	
Wildfire Name	**State**	**Wildfire Name**	**State**
Rattlesnake Creek Fire	ID	Reynolds Lake Fire	ID
Carr Fire	CA	Rattlesnake Creek Fire	ID
Taylor Creek Fire	OR	Keithly Fire	ID
Sharps Fire	ID	Watson Creek Fire	OR
Mendocino Complex Fire	CA	Sheep Creek Fire	NV
Cougar Creek Fire	WA	South Sugarloaf Fire	NV
Goldstone Fire	MT	Watson Creek Fire	OR
Wigwam Fire	MT	Stone Fire	CA
Monument Fire	MT	Watson Creek Fire	OR
Goldstone Fire	MT	Watson Creek Fire	OR
Miriam Fire	WA	Mendocino Complex Fire	CA
Sheep Creek	NV	Tepee Fire	OR
Mendocino Complex Fire	CA		
South Sugarloaf Fire	NV		
Silver Creek Fire	CO		

Table 1. Wildfires flown by WE-CAN and BB-FLUX in 2018. Selected wildfires were field sampled. All wildfires were modelled for source characterization using the Fuel and Fire Tools software.

7.2 Results

The aerial LiDAR acquisition compilation was mapped for the western United States and presented to WE-CAN, BB-FLUX and FIREX-AQ lead scientists. The map was implemented into their wildfire selection criteria application as one determinant of which wildfire plume would be sampled. If a smoke plume is sampled that is located where pre-fire LiDAR mapping has occurred, we will have improved our pre-fire fuels data assessment. If we have the opportunity to fly post-fire LiDAR, our over-all ability to characterize the source and compare with the plume sampled data would be improved (Figure 9). Figures 10 and 11 provide the modeled fuel consumption and emissions data for the wildfires where field data was collected.

The 2019 field data collection for the 2019 FIRE-AQ selected wildfires have been collected, but not reduced and analyzed. The wildfire source modeling for the 2019 FIREX-AQ flights have yet to be completed.

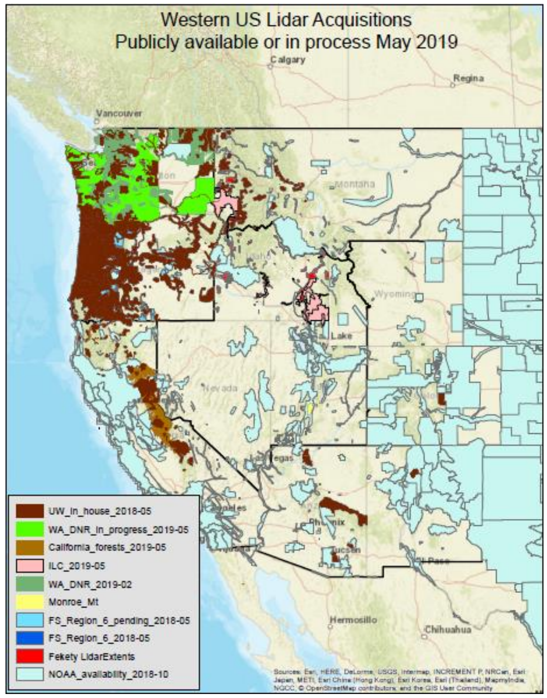

Figure 9. Western United States LiDAR map used for selecting wildfires to sample during the WE-CAN, BB-FLUX and FIREX-AQ project in 2018 and 2019.

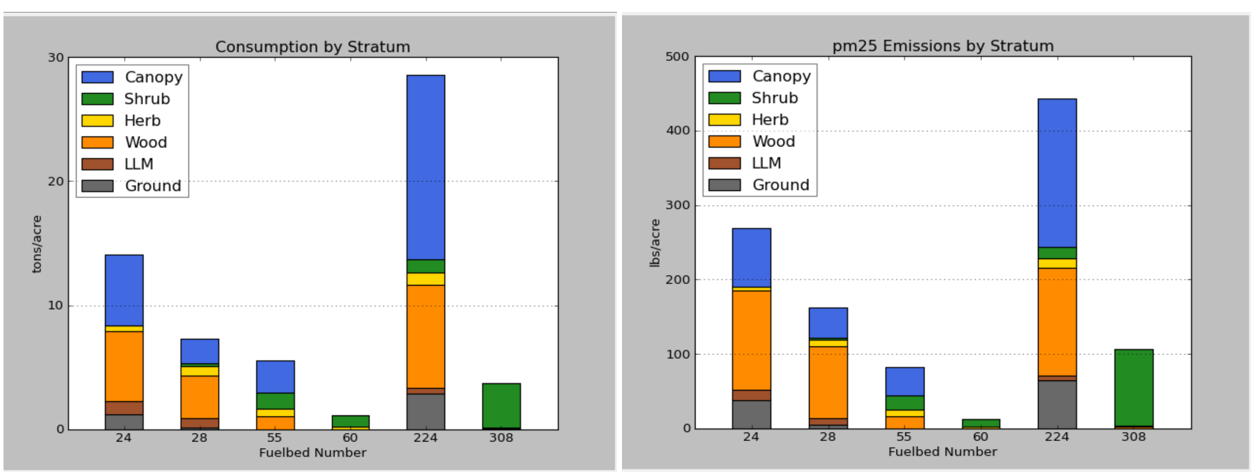

Figure 10. Fuel consumption and PM 2.5 emissions modeled using the FFT and assigned FCCS fuelbeds for the Tepee wildfire.

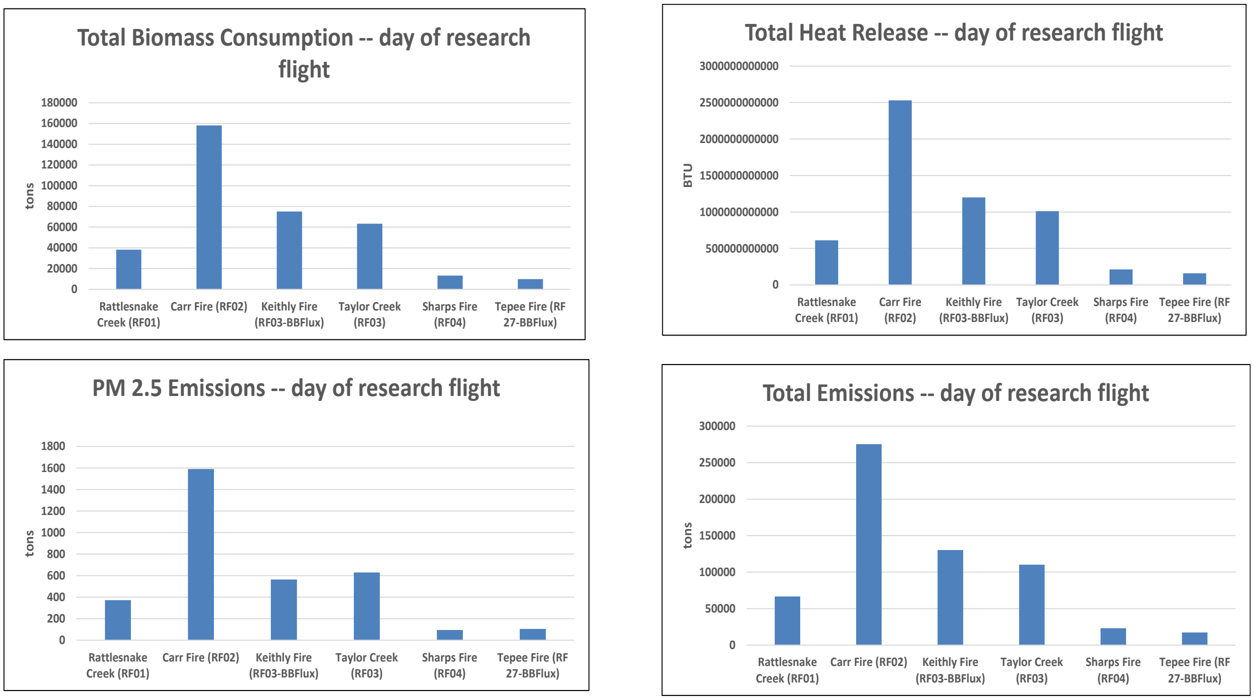

Figure 11. Total fuel consumption, heat release, PM 2.5 emissions and total emissions modelled using FFT for the Rattlesnake, Carr, Keithly, Taylor Creek, Sharps, and Tepee wildfires.

8. Discussion

As wildland fire behavior, fuel consumption, energy release and plume dynamics, smoke dispersion, and atmospheric chemistry models have become more sophisticated, there has been an increasing need for complex datasets that are coordinated, synchronized and comprehensive. Desired metrics range from ground-based observations of fuels, fuel consumption, and fire behavior and energy, to near-source plume dynamics and energy, smoke concentration and trajectories, dispersion, atmospheric chemistry, and smoke aging. FASMEE is designed to provide these integrated observations, and to serve as a template for future campaigns that together will provide the datasets necessary to evaluate and develop next-generation operational fire and smoke modeling systems.

Building on the success and lessons learned from previous fire and atmospheric campaigns such as the Prescribed Fire Combustion and Atmospheric Dynamics Research Experiment (RxCADRE) and Northwest Crown Fire Experiment, the FASMEE project was launched to provide integrated measurements of high-intensity fire behavior and smoke in both the western and eastern regions of the United States. FASMEE takes advantage of past campaigns, including the importance of involving fire scientists and model developers at the inception of measurements campaigns, and the critical value of spatiotemporal synchronization of all measurements identified.

The FASMEE study plan assessment indicated that the Phase 2 data collection would cost approximately 8 million dollars over the course of 5 years. However, only partial funding was available from the JFSP. Consequently, to keep FASMEE moving forward, those funds were leveraged with other agencies, including in-kind support from the National Science Foundation, NOAA, NASA, EPA, and funding from the U.S. Forest Service Pacific Northwest Research Station and the Washington Office. Additionally, many scientists contributed their own time and resources to participate in this effort. This combined support provided continued leadership for FASMEE and initiated a reduced effort for the Phase 2 western wildfire data collection campaign. Although full funding of FASMEE has yet to be secured, the study plan and conceptual plan promise of integrated measurements provide a compelling case for investment in large-scale, comprehensive measurement campaigns of fuel, fire and smoke production.

9. Conclusions Including Key Findings and Progress

Significant advances in our understanding of fire and smoke dynamics as well as our ability to observe, characterize and model fuels, fuel consumption, energy release, fire behavior, plume dynamics, smoke production and aging, and dispersion have been made over the past decade. Advanced model output is now routinely available to managers, as seen with the incorporation, use and adoption of the BlueSky modeling framework and the Interagency Fuel Treatment Decision Support System (IFTDSS). These systems provide value added information but are simplistic in their treatment of complex fire dynamics and need to be thoroughly evaluated and advanced. More complex models, such as coupled fire-atmosphere-chemistry models (e.g., WFR-SFIRE-CHEM, WFDS and FIRETEC) are being developed, but are not in full operative mode currently and will require greater input data. Unfortunately, the lack of observational data means substantial uncertainty about the underlying dynamics and how well these systems can capture them. FASMEE is designed to facilitate the transition of more advanced modeling systems into operational use by supplying critical data necessary to evaluate and advance these systems. The expected outcome from the FASMEE project (assuming adequate funding and support) include:

- Improvements in our scientific knowledge of the physically-coupled fuels-fire-smoke-chemistry system,
- Improved methods for measuring fuels for fire spread, fuel consumption and fire emissions models,
- Insight into processes that drive the spatial organization of fire energy and emissions to help define the transition between fires and plumes that affect air quality, and
- Improvement of existing operational fire and smoke models and the development of new models based on the collection of a unique dataset (fuels, fire, meteorological, smoke plume and chemistry).

The three FASMEE campaigns, as outlined in the study plan deliverable, will provide a set of fully referenced, synchronized fuel, fire behavior and energy, plume dynamics, and meteorological and emission data required for the evaluation and advancement of operational fire and smoke modeling systems in current use. These data will be made available to all individuals through an open data repository designed by geospatial data managers and coordinated with partner agencies to ensure the development of a legacy dataset that can be amplified in subsequent coordinated field campaigns.

9.1 Value for Assessment and Advancement of Operational Fire and Smoke Models

Software tools currently in use today that drive smoke model prediction systems and are expected to use data collected during FASMEE to assess and advance these models. These include modeling systems (e.g., FIRETEC, WFDS, WRF-SFIRE, MesoNH-ForeFire, Daysmoke and the BlueSky framework, WRF-SFIRE and the Community Multiscale Air Quality (CMAQ)) that quantitatively predict smoke and estimates of smoke particulate concentration and trace gases. The significant knowledge gaps in smoke modeling include (1) how the composition and intensity of emissions vary with fuel characteristics and fire behavior, (2) how fire-generated buoyant flow combines with ambient atmospheric conditions to develop smoke plumes, and (3) understanding of post-emission chemical processes that can rapidly cause large changes in the concentrations of fine PM and O_3. The only means to satisfactorily address these gaps is through sufficient measurements of area burned, fuels, fuel consumption, fire behavior, fire-generated heat, and smoke production, transport, and evolution, which can then be used to test model parameterizations and evaluate the results.

The FASMEE-recommended measurement suite is designed to collect data for the critical factors in the production, transport and chemical evolution of smoke. Phase 2 recommendations emphasize measurements of high-volume smoke production from burning in heavy fuels that produce multiple plume cores and significant vertical plume development. The mass of smoke produced and the plume dynamics will mimic those of a robust wildfire, producing a plume sufficiently concentrated to observe photochemical evolution and atmospheric transport similar to that of wildfires. The resulting data can be applied to nearly any modeling system with a smoke prediction component.

9.2 Benefit to Fire and Smoke Management Community

The measurement suite planned for FASMEE provides quantitative information for improvements and development of many coupled fire-atmosphere models and will provide critical datasets for developing the next generation of operational models of fire and smoke. For models currently used for research-based analyses of fire, FASMEE will provide uniquely integrated and comprehensive datasets to advance our understanding of the complex fire-atmosphere system. Integrated measurements from the FASMEE campaign will enable evaluations of (1) how well specific models perform under real-world applications, (2) the level of model uncertainties, and (3) what key sources of these uncertainties need improvements. Observation-based phenomenological characterization can help to assess whether intermediate-complexity and physics-based models are capturing coupled fire-atmosphere behavior that is critical to the simulation of high-intensity fires in complex terrain.

9.3 Broader Impact onto Decision Makers and Society

Many sources for smoke information are now available to managers, including both web-based and downloadable models and datasets. These include simple screening tools, ventilation indices, web-based systems, real-time smoke forecasts, and daily atmospheric chemistry modeling. These resources are commonly used to help mitigate smoke effects, which can be numerous. Smoke from wildfires has been associated with increased physician and emergency room visits, hospital admissions, and mortality. Illnesses and infectious disease complications (e.g. Covid-19) attributed to smoke exposure can also result in hospital admissions, absenteeism from work and school, affecting economic productivity and educational achievement. The FASMEE project aims to provide data to improve publicly available information generated from smoke models for the benefits of protecting public health and welfare through more accurate smoke predictions and warnings.

The scope and design of the FASMEE field experiments allows for interagency collaboration and partnerships. For example, agency programs that focus on air quality could use methods similar to those recommended for the Phase 2 measurement campaign to characterize fuels, fire behavior, and plume dynamics.

This experiment will serve as a training opportunity for investigators in the earlier stages of their careers to observe and participate in large research burns that involve close coordination among managers, researchers, and operations communities. In the same way that the research outcomes of FASMEE benefit research support to fire management in the coming decades, the experience provided to early-career personnel involved in FASMEE will benefit the research community's ability to plan, coordinate and conduct ambitious projects in other areas of fire science well into the future.

9.4 Broader Effects on Other Disciplines

Data from the FASMEE research burns will provide a large data set that will be available for use by many other disciplines besides fire and smoke science. Ecological measurements could be made pre- and post-burn in the context of detailed known fire environment and burning conditions that can be associated with ecological effects. Documentation of FASMEE burns will include spatiotemporal mapping of fuels, fuel consumption, fire behavior, heat release and duration, plume development to facilitate broad use of the datasets collected during these campaigns.

Depending on the ecological focus, additional insights provided by fuel consumption and heat duration data from the FASMEE could include studies of tree mortality or aspen spouting. U.S. Geological Survey Forest and Rangeland Ecosystem Science Center studies of soil and erosion will benefit from detailed observations of pre- and post-fire fuel characterization and energy release over time. Although FASMEE will not provide the resources to assist with or participate in such studies, the FASMEE leadership team and investigators have expressed a desire to cooperate with interested non-FASMEE teams in conducting work that will not interfere with FASMEE logistics or add personnel or complexity during the burns themselves.

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Appendix A Contact information for Key Project Personnel

Roger Ottmar, Project Principal Investigator
Pacific Wildland Fire Sciences Laboratory
Pacific Northwest Research Station
400 North 34th Street, Suite 201
Seattle, WA 98103
E-mail: roger.ottmar@usda.gov
Office phone: 206-732-7826
Cell phone: 206-849-3172

Narasimhan (Sim) Larkin, Co-Principal Investigator
Pacific Wildland Fire Sciences Laboratory
Pacific Northwest Research Station
400 North 34th Street, Suite 201
Seattle, WA 98103
E-mail: sim_larkin@firenet.gov; sim.larkin@usda.gov
Office phone: 206-732-7826
Cell phone: 206-321-2013

Tim Brown, Co-Principal Investigator
Desert Research Institute
2215 Raggio Parkway
Reno, NV 89512
E-mail: tim.brown@dri.edu
Office phone: 775-674-7090
Cell phone: 775-530-3116

Nancy French, Co-Principal Investigator
Michigan Tech Research Institute
3600 Green Court, Suite 100
Ann Arbor, MI 48105
E-mail: nhfrench@mtu.edu
Office phone: 734-913-6844
Cell phone: 734-913-6844

Appendix B. List of Completed/Planned Scientific/Technical Publications/Science Delivery Products

1. FASMEE Study Plan Publications

- Fire and Smoke Model Evaluation Experiment (FASMEE) Study Plan: https://drive.google.com/file/d/1_6132DnJoJ3zbDO-XdHMA413895AT-ws/view

- Prichard, S. J., Larkin, N. S., Ottmar, R. D., French, N. H., Brown, T. J., Baker, K., Clements, C., Dickinson, M., Hudak, A., Kochanski, A., Linn, R., Liu, Y., Potter, B., Mell, W. E., Tanzer, D., Urbanski, S., Watts, A. C. (2019). The Fire and Smoke Model Evaluation Experiment: A plan for integrated, large fire-atmosphere field campaigns, *Atmosphere*, 10, (2), 66, https://doi.org/10.3390/atmos10020066. https://www.fs.usda.gov/treesearch/pubs/57718

- Ottmar, R. D., Larkin, N. S., Brown, T. J., French, N. H., Prichard, S. J., Watts, Adam. (In Review) Fire and Smoke Model Evaluation Experiment (FASMEE): Development of an integrated experiment for advancing operational wildland fire and smoke modelling. To be published as a Pacific Northwest Research Station General Technical Report.

- Liu, Y., Kochanski, A., Baker, K. R., Mell, W., Linn, R., Paugam, R., Mandel, J., Fournier, A., Jenkins, M. A., Goodrick, S., Achtemeier, G., Zhao, F., Ottmar, R., French, N. H., Larkin, N., Brown, T. J., Hudak, A., Dickinson, M., Potter, B., Clements, C., Urbanski, S., Prichard, S., Watts, A. C., McNamara, D. (2019). Fire behaviour and smoke modelling: Model improvement and measurement needs for next-generation smoke research and forecasting systems, *International Journal of Wildland Fire*, 28, 570-588, doi: 10.1071/WF18204

2. Publications for Western Wildfire Campaign

- Filippelli, S., M.J. Falkowski, A.T. Hudak, P.A. Fekety, J.C. Vogeler, A.H. Khalyani, B.M. Rau and E.K. Strand. (2020) Monitoring pinyon-juniper cover and aboveground biomass across the Great Basin. *Environmental Research Letters* 15: 025004. https://doi.org/10.1088/1748-9326/ab6785.

- Hiers, J.K., J.J. O'Brien, J.M. Varner, B.W. Butler, M. Dickinson, J. Furman, M. Gallagher, D. Godwin, S.L. Goodrick, S.M. Hood, A. Hudak, L.N. Kobziar, R. Linn, E.L. Loudermilk, S. McCaffrey, K. Robertson, E.M. Rowell, N. Skowronski, A.C. Watts and K.M. Yedinak. (2020) Prescribed fire science: the case for a refined research agenda. *Fire Ecology* 16: 11. https://doi.org/10.1186/s42408-020-0070-8.

- Hudak, A.T., P.A. Fekety, M.J. Falkowski, R.E. Kennedy, N.L. Crookston, G. Domke, A.M.S. Smith, V. Kane, R. McGaughey, P. Gould, N. Glenn, J. Dong. (In Press) A carbon monitoring system for mapping regional, annual aboveground biomass across the northwestern USA. Special Issue on "Carbon Monitoring Systems Research and Applications". Environmental Research Letters (CMS Special Issue).

- Mauro, F., A. Hudak, P. Fekety and M. Gregory. (In prep) Prediction of forest fuel attributes from LiDAR data, topographic attributes and climate variables for a large area in Oregon (USA). Forest Ecology and Management.

- McCarley, T.R., A.T. Hudak, A.M. Sparks, L. Boschetti and A.J.H. Meddens. (In review) Assessing methods for measuring biomass consumption using bi-temporal LiDAR and demonstrating linkage with energy release. Remote Sensing of Environment.

- McGaughey, R.J. 2018. FUSION/LDV: Software for LIDAR Data Analysis and Visualization, v3.80. USDA Forest Service, Pacific Northwest Research Station, Seattle, WA.

3. Joint Fire Science Program Assistance

- Ottmar, Roger; Larkin, Sim, Brown, Tim. 2015. Notice of Intent for 2016 Funding Opportunity for FASMEE Phase 2 observational measurement collection

- Ottmar, Roger, Larkin, Sim, Brown, Tim. 2015. Funding Opportunity Notice for fall of 2016 for FASMEE Phase 2 operational measurement collection

4. Presentations

- Hudak, A., R. McCarley, B. Bright, M. Corrao, R. Ottmar, N. French and A. Soja. 2020. 2020. FASMEE Western Wildfire Campaign: Fuel consumption maps to reduce uncertainties in emissions. Third International Smoke Symposium, Raleigh, North Carolina, 20-23 Apr 2020. (virtual oral presentation, published abstract).

- Hudak, A., R. McCarley, P. Fekety, F. Mauro, V. Kane, J. Restaino, R. Ottmar, E. Fischer, R. Volkamer, T. Goulden and B. Haas. 2019. FASMEE Western Wildfire Campaign: Modeled, ground, and lidar based estimates of fuel consumption. 8th International Association for Fire Ecology Congress, Tucson, Arizona, 18-22 Nov 2019. (oral presentation, published abstract).

- Hudak, A., P. Fekety, S. Filippelli, M. Falkowski, R. Kennedy and V. Kane. 2019. Annual (2000-2016) maps of aboveground biomass in the Northwestern USA. International Union of Forestry Research Organizations World Congress, Curitiba, Parana, Brazil, 29 Sep – 5 Oct 2019. (oral presentation, published abstract).

- Hudak, A., P. Fekety, M. Falkowski, R. Kennedy and V. Kane. 2019. Upscaling of project-level, lidar-based forest inventories for regional biomass mapping in the northwestern USA. National Silviculture Workshop, Bemidji, Minnesota, 21-23 May 2019. (poster, published abstract).

- Hudak, A., B. Bright, R. McCarley, A. Kato, L. Loudermilk, C. Hawley, G. Prata, S. Prichard, J. Restaino, R. Ottmar and D. Weise. 2019. Estimating fuel consumption at multiple scales from pre- and post-fire TLS and ALS. Silvilaser Conference, Foz do Iguacu, Parana, Brazil, 8-10 Oct 2019. (oral presentation, published abstract).

- Loudermilk, L. A. Hudak, S. Flanagan, S. Goodrick, J. O'Brien and K. Hiers. 2020. Coarse-scale 3D fuel mapping for operational use in next-generation fire-atmosphere fire behavior models. USFS-NASA Joint Applications Workshop Virtual Pitchfest, 2-3 Jun 2020. (virtual oral presentation, published abstract).

- McCarley, T.R. and A.T. Hudak. 2019. Quantifying interactions between wildfire, prior mountain beetle outbreak and harvest on forest aboveground biomass from bi-temporal lidar. 8th International Association for Fire Ecology Congress, Tucson, Arizona, 18-22 Nov 2019. (oral presentation, published abstract).

- McCarley, T.R., A.T. Hudak, A.M. Sparks, L. Boschetti and A.J. Meddens. 2018. Quantifying fuel consumption for two western U.S. fires using repeat LiDAR. American Geophysical Union Fall Meeting, Washington, DC, 10-14 Dec 2018. (oral presentation, published abstract).

- Ottmar, Roger D. 2020. The Fire and Smoke Model Evaluation Experiment (FASMEE)- An Overview of the Project. Third International Smoke Symposium, Raleigh, North Carolina, 20-23 Apr 2020. (virtual oral presentation, published abstract).

- Ottmar, Roger D. 2020. Western Wildfires and Southwest Campaign: Characterizing the source for fuels, fuel consumption, and total smoke. 3rd International Smoke Symposium, Raleigh, NC. Third International Smoke Symposium, Raleigh, North Carolina, 20-23 Apr 2020. (virtual oral presentation, published abstract).

- Ottmar, Roger. 2018. Fire and Smoke Model Evaluation Experiment, 2nd International Smoke Symposium, Long Beach, CA. (virtual oral presentation, published abstract).

- Ottmar, Roger. 2016. Overview of Fire and Smoke Model Evaluation Experiment (FASMEE), 2nd International Smoke Symposium, November 14-17, 2016. Long Beach, CA

- Ottmar, Roger. 2015. Fire and Smoke Model Evaluation Experiment FASMEE), 5th International Fire Behavior and Fuels Conference, April 11-15, 2015. Portland, OR Ottmar, Roger. 2018. Fire and Smoke Model Evaluation Experiment western wildfire campaign, The Fire Continuum Conference, May 21-24, 2018, Missoula, MT.

- Ottmar, Roger D. 2015-2019. Presented FASMEE at 30 Rx410 (Smoke Management) classes from 2015-2019.

- Soja, A., E. Gargulinski, E. Wiggins, J. McCarty, A. Hudak, E. Rintsch, K. Hiers, C. Schmidt and J. 2020. Fain. Fueled from below: linking fire, fuels, and weather to atmospheric chemistry. Third International Smoke Symposium, Raleigh, North Carolina, 20-23 Apr 2020. (virtual oral presentation, published abstract).

- Volkamer, R.M., N. Kille, C. Lee, K.J. Zarzana, T.K. Koenig, B. Howard, R. Nutter, C. Knote, T.L. Campos, D.M. Plummer, L. Oolman, M. Deng, Z. Wang, R. Ahmadov, R.B. Pierce, A. Zahn[4], F. Obersteiner, T. Goulden, B. Hass, E.V. Fischer, A.T. Hudak, J. Restaino and R.D. Ottmar. 2019. The BB-FLUX project: How much fuel goes up in smoke? American Geophysical Union Annual Meeting, San Francisco, California, 9-13 Dec 2019. (oral presentation, published abstract).

5. Invited Presentation

- Halverson, K. and A. Hudak. 2019. Applications of carbon and biomass data in the USDA Forest Service. Carbon Monitoring Systems Applications Workshop, La Jolla, California, 12 Nov 2019. (oral presentation).

- Hudak, A.T. and K. Halverson. 2020. Rating the effectiveness of treatments: biomass products. USFS Region 4 Information Management Meeting, Ogden, Utah, 13-15 Apr 2020. (virtual oral presentation).

- Hudak, A. 2019. Carbon Monitoring System (CMS) Phases 1 and 2. Operational Lidar Inventory Workshop, Olympia, Washington, 5 Mar 2020. (oral presentation).

- Hudak, A. 2019. A bottom-up, stakeholder-driven CMS for regional biomass carbon dynamics: Phase 2. Precision Forestry Cooperative Board Meeting, Seattle, Washington, 13 Dec 2019 (video presentation).

- Hudak, A., J. Vogeler, P. Fekety, S. Filippelli, V. Kane, R. Kennedy, C. Babcock, G. Domke, A. Meddens, F. Mauro, M. Corrao, K. Halverson, B. Bright. 2019. A bottom-up, stakeholder-driven CMS for regional biomass carbon dynamics: Phase 2. Carbon Monitoring Systems Science Team Meeting, La Jolla, California, 13-14 Nov 2019 (poster).

- Hudak, A.T., P. Fekety, V. Kane, R. Kennedy, S. Filippelli, M. Falkowski, G. Domke, A. Smith, W. Tinkham, N. Crookston, M. Corrao, B. Bright, D. Churchill, J. Kane, R. McGaughey and J. Dong. 2019. Prototyping a methodology to develop regional-scale forest aboveground biomass carbon maps predicted from Landsat time series, trained from field and lidar data collections, and independently validated with FIA data. Carbon Monitoring Systems Science Team Meeting, La Jolla, California, 13-14 Nov 2019 (poster).

- Hudak, A. 2019. A bottom-up, stakeholder-driven CMS for regional biomass carbon dynamics: Phase 2. Carbon Monitoring Systems Science Team Meeting, La Jolla, California, 13 Nov 2019 (oral presentation).

- Hudak, A., R. McCarley, P. Fekety, B. Bright, A. Kato, L. Loudermilk, E. Rowell, C. Silva, J. Restaino, S. Prichard, R. Ottmar and D. Weise. 2019. Quantifying biomass and biomass change at multiple scales from TLS and ALS. Invited seminar, Universiti Kebangsaan Malaysia, Kuala Lumpur, Malaysia, 1 Aug 2019. (oral presentation, published abstract).

- Hudak, A., R. Kennedy, P. Fekety, S. Filippelli, M. Falkowski and V. Kane. 2019. Mapping forest aboveground biomass annually (2000-2016) from Landsat time series. Keynote for 6th International Conference on Space Science and Communication, Johor Bahru, Malaysia, 29 Jul 2019. (oral presentation, published abstract).

- Hudak, A., R. McCarley, J. Restaino, R. Ottmar, T. Goulden, R. Volkamer and E. Fischer. 2019. Fuel consumption and emissions on the five WE-CAN/BB-FLUX wildfires selected for field and airborne LiDAR measurements. Western Wildfire Smoke Workshop, Boulder, Colorado, 23-25 Apr 2019. (oral presentation).

- Hudak, A., P. Fekety, S. Filippelli, M. Falkowski, R. Kennedy, V. Kane, G. Domke, N. Crookston and A. Smith. 2019. Monitoring current and future forest carbon stores in the northwestern USA from Landsat time series, airborne lidar, and inventory plot data. Invited seminar, Barbara Wheatland Seminar Series, University of Maine, Orono, Maine, 13 Mar 2019. (oral presentation, published abstract).

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